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DOCTORAL THESIS

Human-centred design for advanced services: A multidimensional design methodology

NGUYEN NGOC HIEN

DimanD

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Thesis Directors:
Ganix Lasa Erle
Ion Iriarte Azpiazu

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Statement of originality

I, Hien Nguyen Ngoc, declare that this thesis has not been previously submitted to obtain another degree or professional qualification. The ideas, formulations, images, illustrations taken from other sources have been duly cited and referenced. The publications used to compile this thesis are accredited to my work with the following roles:

Hien Nguyen Ngoc performed all research activities: research conceptualization and methodology, material preparation, survey design and data collection, analysis, visualization and programming, manuscript writing and submission, research planning and monitoring. Ganix Lasa and Ion Iriarte supervised and approved the research activities. Ariane Atxa improved the visualization aspects of two publications presented in Chapter 4 and Chapter 5. Gorka Unamuno, Gurutz Galfarsoro were industrial advisors who evaluated and consulted research activities and results of two publications presented in Chapter 4 and Chapter 5.

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Abstract

Today, product-oriented companies are discovering new value creation methods that enable them to increase customer satisfaction, market share and competitiveness for improved economic returns and sustainability. New value creation can be achieved with new business models that help these companies to extend their services by means of their product-service systems (PSS), that is, systems representing bundles of products and services. This extension process known as servitization where PSS are often cited as the offering of a combination of products and services bundled together to enhance customer satisfaction across disciplines. As a special case of PSS, advanced services offer feature risk and revenue sharing agreements with customers over the life cycle of the service. The idea of advanced services is to offer not only a product (by ownership), but also its performance (e.g., pay-per-performance) and usage (e.g., pay-per-use) as a bundle of products and services, enabling companies' value chains to be extended.

In order to design for these advanced services, a structural human-centred design (HCD) methodology is required to reflect the life-cycle service design, central roles of human actors and then enable effective service delivery. In literature; however, human factors are not often addressed, even though the design of advanced services requires human-centred thinking. Moreover, a wide array of studies in design methodologies for advanced services has been created and published, but they are subsequently disconnected from others. These existing methodologies are limited to partially and/or individually addressing one or some key design elements, e.g., life-cycle service design, or involvement of stakeholder networks, hence causing confusion in practice and resulting in an ineffective implementation. As an effect, the application of these studies in industry and research alike is not continuously adopted while the network of studies is scattered and diffused without a comprehensive accumulating structure.

To advance the body of research, this thesis aims to (i) identify key design elements of an effective HCD methodology for advanced services, and (ii) develop a conceptual multidimensional design methodology, called DIMAND for short, that incorporates the identified key design elements and their relations in a single-view structure in accordance with a human-centric approach. The first aim is addressed through a systematic literature review of case studies in HCD in industry 4.0, revealing key design elements as success design factors of an effective HCD methodology. Based on the findings, DIMAND was conceptually developed through systematic reviews and structured analysis of existing design methodologies, as well as an elicitation of expert knowledge in the domain through the analytical hierarchy process (AHP). Specifically, DIMAND encapsulates the (i) life-cycle service design interrelated with other key design elements—(ii) stakeholder networks, (iii) new service development methods, and (iv) design skills—that must be considered to develop effective advanced service design.

As a result, this thesis presents DIMAND in accordance with HCD for advanced services, offering a novel and holistic guideline for design practitioners and engineers to obtain coherence in all the life-cycle design processes. During the life-cycle service design, DIMAND takes simultaneously the key design elements and their relations into account, making the design of advanced services more practical. Finally, this thesis concludes with future research agenda.

Resumen

Actualmente, las empresas orientadas al producto están descubriendo nuevos métodos de creación de valor que les permiten aumentar la satisfacción del cliente, la cuota de mercado y la competitividad para mejorar la rentabilidad económica y la sostenibilidad. La nueva creación de valor puede lograrse con nuevos modelos de negocio que ayuden a estas empresas a ampliar sus servicios mediante sus sistemas producto-servicio (PSS), es decir, sistemas que representan paquetes de productos y servicios. Este proceso de extensión se denomina servitización, donde los PSS suelen ser citados como la oferta de una combinación de productos y servicios agrupados para mejorar la satisfacción del cliente en todas las disciplinas. Como caso especial de los PSS, los servicios avanzados ofrecen acuerdos de distribución de riesgos e ingresos con los clientes durante el ciclo de vida del servicio. La idea de los servicios avanzados es ofrecer no sólo un producto (por propiedad), sino también su prestación (por ejemplo, pago por prestaciones) y uso (por ejemplo, pago por uso) como un paquete de productos y servicios, lo que permite ampliar las cadenas de valor de las empresas.

Para diseñar estos servicios avanzados, se requiere una metodología de diseño estructural centrado en las personas (HCD) que refleje el diseño del servicio a lo largo del ciclo de vida, los roles centrales de los actores humanos y que después permita una prestación eficaz del servicio. Sin embargo, en la literatura no se suelen abordar los factores humanos, a pesar de que el diseño de los servicios avanzados requiere un pensamiento centrado en las personas. Además, se ha creado y publicado un amplio abanico de estudios sobre metodologías de diseño de servicios avanzados, pero se encuentran desconectados entre sí. Estas metodologías existentes se limitan a tratar parcial y/o individualmente uno o algunos elementos clave del diseño, por ejemplo, el diseño del ciclo de vida del servicio o la participación de las redes de stakeholders, lo que provoca confusión en la práctica y da lugar a una implementación ineficaz que conduce una " paradoja del servicio ". Como consecuencia, la aplicación de estos estudios tanto en la industria como en la investigación no se adopta de forma continua, mientras que la red de estudios está dispersa y difusa sin una estructura acumulativa global.

Para avanzar en el conjunto de las investigaciones, esta tesis tiene como objetivo (i) identificar los elementos clave de diseño de una metodología HCD eficaz para los servicios avanzados, y (ii) desarrollar una metodología de diseño multidimensional conceptual, llamada DIMAND abreviadamente, que incorpora los elementos clave de diseño identificados y sus relaciones en una estructura de vista única de acuerdo con un enfoque centrado en las personas. El primer objetivo se aborda a través de una revisión sistemática de la literatura sobre estudios de casos de HCD en la industria 4.0, revelando los elementos clave del diseño como factores de diseño exitosos de una metodología HCD eficaz. Basándose en los resultados, DIMAND se ha desarrollado conceptualmente a través de revisiones sistemáticas y análisis estructurados de las metodologías de diseño existentes, así como una elicitación del conocimiento de los expertos en el dominio a través del proceso de jerarquía analítica (AHP). En concreto, DIMAND encapsula el (i) diseño de servicios del ciclo de vida interrelacionado con otros elementos clave del diseño — (ii) redes de stakeholders, (iii) nuevos métodos de desarrollo de servicios, y (iv) habilidades de diseño—que deben ser considerados para desarrollar un diseño de servicios avanzado efectivo.

Por consiguiente, esta tesis presenta DIMAND en conformidad con el HCD para servicios avanzados, ofreciendo una guía novedosa y holística para que los practicantes e ingenieros de diseño obtengan coherencia en todos los procesos de diseño del ciclo de vida. Durante el diseño del ciclo de vida del servicio, DIMAND tiene en cuenta simultáneamente los elementos clave del diseño y sus relaciones, haciendo que el diseño de los servicios avanzados sea más práctico. Por último, esta tesis concluye con una agenda de investigación futura.

Laburpena

Gaur egun, produktura bideratutako enpresak balioa sortzeko metodo berriak aurkitzen ari dira, bezeroen gogobetetzea, merkatu-kuota eta lehiakortasuna handitu nahi dutelarik, errentagarritasun ekonomikoa eta jasangarritasuna hobetzeko. Balio-sorkuntza berria produktu-zerbitzu sistemen bidez (PSS) haien zerbitzuak zabaltzen laguntzen duten negozio eredu berriekin lor daiteke, hau da, produktu- eta zerbitzu-paketeak irudikatzen dituzten sistemekin. Hedapen prozesu horri zerbitizazioa deritzo, eta, bertan, PSSak bezeroen gogobetetasuna diziplina guztietan areagotzeko produktu eta zerbitzuen konbinazio gisa aipatzen dira. PSSren kasu berezi gisa, zerbitzu aurreratuek arrisku- eta diru- banaketa akordioak eskaintzen dituzte bezeroekin zerbitzuaren bizi-zikloan zehar. Zerbitzu aurreratuen funtsa, porduktu bat (jabetzaren arabera) ez ezik, haren prestazioa (adb. prestazioen araberako ordainketa) eta erabilera (adb. erabileraren araberako ordainketa) ere produktu eta zerbitzu pakete gisa eskaintzea da, enpresen balio-kateak hedatzea ahalbidetuz.

Zerbitzu aurreratu hauek diseinatzeko, pertsonak ardatz dituen diseinu egiturako metodologia bat behar da (HCD), bizi-zikloan zehar zerbitzuaren diseinua eta giza aktoreen rol nagusiak islatuko dituena, eta, ondoren, zerbitzua eraginkortasunez ematea ahalbidetuko duena. Dena den, literaturan ez dira giza faktoreak lantzen, nahiz eta zerbitzu aurreratuen diseinuak pertsonengan oinarritutako pentsamendua eskatzen duen. Gainera, zerbitzu aurreratuak diseinatzeko metodologiei buruzko azterlan sorta zabala sortu eta argitaratu da, baina elkarrekin deskonektatuta daude. Dauden metodologia horiek diseinuaren funtsezko elementu bat edo batzuk (adibidez, zerbitzuaren bizi-zikloaren diseinua edo stakeholder sareen parte-hartzea) partzialki eta/edo banaka tratatzera mugatzen dira. Horrek nahasmena eragiten du praktikan, eta "zerbitzuaren paradoxa" dakarren inplementazio ez-eraginkorra sortzen du. Horren ondorioz, ikasketa-sarea sakabanatuta eta lausotuta dagoen bitartean, egitura metatzaile globalik gabe, azterlan hauen aplikazioa ez da ez industrian ezta ikerketan ere modu jarraituan ematen.

Ikerketetan aurrera egiteko, tesi honen helburua da (i) zerbitzu aurreratuetarako HCD metodologia eraginkor baten diseinuaren funtsezko elementuak identifikatzea, eta (ii) diseinu multidimentsional kontzeptualaren metodologia garatzea, DIMAND izenean laburtuta, identifikatutako diseinuaren funtsezko elementuak eta horien arteko erlazioak pertsonak ardatz dituen ikuspegi-egitura bakar batean barne hartzen dituena. Lehenengo helburuari heltzeko, 4.0 industriako HCD kasuen azterketei buruzko literatura sistematikoki berrikusten da, diseinuaren funtsezko elementuak HCD metodologia eraginkor baten diseinu-faktore arrakastatsu gisa azaleratuz. Emaitzetan oinarrituta, DIMAND kontzeptualki garatu da, dauden diseinu-metodologien berrikuspen sistematikoen eta analisi egituratuen bidez, bai eta adituek domeinuan duten ezagutza elikatuz ere, hierarkia analitikoko prozesuaren bidez (AHP). Zehazki, DIMANDEK hurrengo puntuak kapsulatzen ditu: (i) bizi-zikloaren zerbitzuen diseinua, diseinuaren funtsezko beste elementu batzuekin lotuta; — (ii) stakeholder sareak; (iii) zerbitzuak garatzeko metodo berriak; eta (iv) diseinu-trebetasunak — zerbitzu-diseinu aurreratu eraginkorra garatzeko kontuan hartu beharrekoak.

Beraz, tesi honek DIMAND aurkezten du, zerbitzu aurreratuetarako HCDaren arabera, gida berritzaile eta holistiko bat eskainiz diseinuko praktikatzaile eta ingeniariek koherentzia lor dezaten bizi-zikloaren diseinu-prozesu guztietan. Zerbitzuaren bizi-zikloa diseinatzean, DIMANDek aldi berean kontuan hartzen ditu diseinuaren funtsezko elementuak eta horien arteko harremanak, zerbitzu aurreratuen diseinua praktikoagoa izan dadin. Azkenik, tesi hau etorkizuneko ikerketa-agenda batekin amaitzen da.

Publications related to this thesis

Journal articles:

i. **Nguyen, N. H.,** Lasa, G., & Iriarte, I. (2022). Human-centred design in industry 4.0: case study review and opportunities for future research. *Journal of Intelligent Manufacturing*, *33*(1), 35–76. https://doi.org/10.1007/s10845-021-01796-x

ii. **Nguyen, N. H.,** Lasa, G., Iriarte, I., Atxa, A., Unamuno, G., & Galfarsoro, G. (2022a). Datasets of skills-rating questionnaires for advanced service design through expert knowledge elicitation. *Scientific Data*, *9*(1), 321. https://doi.org/10.1038/s41597-022-01421-3

iii. **Nguyen, H. N.,** Lasa, G., Iriarte, I., Atxa, A., Unamuno, G., & Galfarsoro, G. (2022b). Human-centred design for advanced services: A multidimensional design methodology. *Advanced Engineering Informatics*, *53*(July), 101720. https://doi.org/10.1016/j.aei.2022.101720

Conference articles:

iv. **Nguyen, H. N.,** Lasa, G., & Iriarte, I. (2021). Human-Centred Design in the context of Servitization in Industry 4.0: A Collaborative Approach. 30th RESER International Congress. Alcalá de Henares, 21-22 Jan. 2021. http://hdl.handle.net/20.500.11984/5314

v. **Nguyen, N. H.,** Lasa, G., Iriarte, I., & Unamuno, G. (2022). An overview of Industry 4.0 Applications for Advanced Maintenance Services. *Procedia Computer Science*, *200*, 803–810. https://doi.org/10.1016/j.procs.2022.01.277

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GLOSSARY

LIST OF ABBREVIATIONS

AHP	Analytical Hierarchy Process
DIMAND	A proposed HCD methodology for advanced services
HCD	Human Centred Design
HMI	Human Machine Interface
HRC	Human Robot Collaboration
HioTL	Human-in-on-The-Loop
PSS	Product Service Systems
SUS	Simplified System Usability Scale
UCD	User Centred Design

CHAPTER 1

Introduction

1. Introduction

This chapter presents the thesis motivation in the context of human-centred design (HCD), taking into account industry 4.0 scenarios. Based on a systematic literature review in the context, the thesis focuses on HCD for advanced services, which are a special case of product-service systems (PSS) that are emerging in the field. Through the review, the present chapter defines the overall objective and research questions. Subsequently, the research structure and process are presented.

1.1. Context and motivation

Human-centred design in Industry 4.0

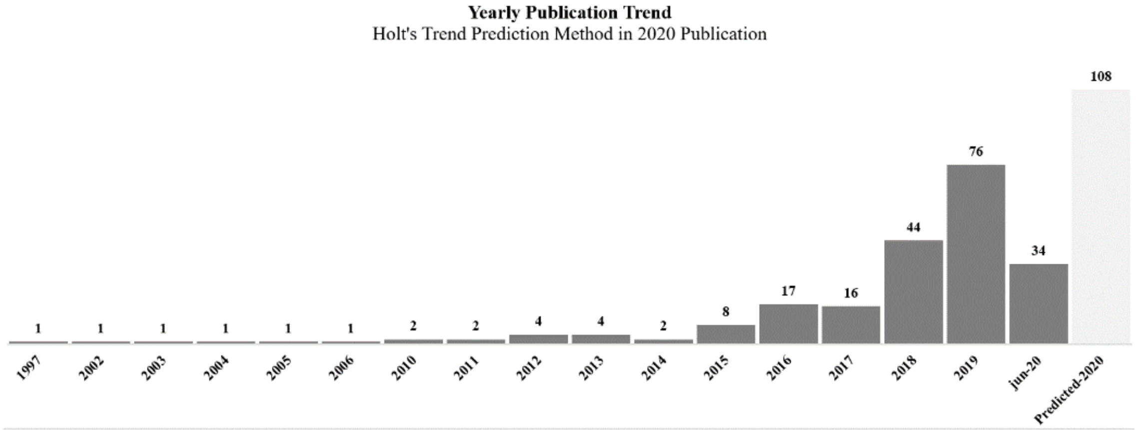
A challenge of manufacturing today is adapting to an increasingly fluctuating environment and diverse changes (e.g., short product life cycles, small production batch sizes, dynamic product variants associated with increasing complexity) to meet the demands of the market (Benabdellah et al., 2019; Kuhnle et al., 2021; Ma et al., 2017; Prinz et al., 2019; Windt et al., 2008; L. Wu et al., 2016; Zhu et al., 2015). To manage these dynamics, the industrial concept of Industry 4.0 has come about and has been accepted in both research and industry, a trend linked to digitalization and smart systems that could enable factories to improve economic returns (e..g, productivity and quality improvement) and sustainability (e.g., decreasing energy consumption) (García-Magro & Soriano-Pinar, 2019; Järvenpää et al., 2019; Napoleone et al., 2020; Oztemel & Gursev, 2020; Park & Tran, 2014). Although the adoption of Industry 4.0 in manufacturing reveals positive outcomes, the increased complexity as a collateral effect has also brought many challenges (Bednar & Welch, 2020; Cohen et al., 2019; Fernandez-Carames & Fraga-Lamas, 2018; D. Mourtzis, 2016; Dimitris Mourtzis et al., 2018). One of the challenges is to put humans properly at the centre of smart manufacturing design; an approach to address this challenge is known as HCD. According to the International Organization for Standardization (2019), HCD is a multidisciplinary approach incorporating human factors and ergonomics knowledge and techniques to make systems usable.

Numerous contributions have been written on Industry 4.0 areas; however, the majority of them focus on the technical aspects in which human factors (physical, cognitive and/or social aspects) are commonly underestimated (Bhamare et al., 2020; Grandi et al., 2020; Pacaux-Lemoine et al., 2017; Peruzzini et al., 2019). There is an increasing concern about how human factors are barely considered in design for products and/or services and poorly addressed in manufacturing, causing complex problems with often unknown consequences across different industrial contexts: nuclear accidents (L. Wu et al., 2016), market failures in new product development (García-Magro & Soriano-Pinar, 2019), robotic-surgery-related adversities (Varshney & Alemzadeh, 2017), technological accidents during machine manipulation (Pacaux-Lemoine et al., 2017), and interaction issues among humans and smart systems (Rogers et al., 2019; Streitz, 2019). Recently, the European Commission has embraced the concept of Industry 5.0, which aims to create industries that are human-centred, sustainable, and resilient (Breque et al., 2021). Nevertheless, human factors still remains a significant challenge for the emerging research scheme in Industry 5.0, which aims to create smart environments that prioritize human well-being while maintaining manufacturing performance (Coronado et al., 2022).

The phenomenon of Industry 4.0 reflects contemporary design contexts that frequently contain complex interdependencies of human and non-human actors—internet of thing (IoT) devices, digital and physical environments—shaping the framework of human roles and socio-technical systems (Cimini et al., 2020; Coulton & Lindley, 2019; Jwo et al., 2021; Kong et al., 2019; Kymäläinen et al., 2017). However, this does not mean that the existing concepts of design—for example, design for manufacturing and assembly (Favi et al., 2021), or a traditional design process that considers existing solutions to fulfil the needs of the largest group (Lorentzen & Hedvall, 2018)—are redundant. They have evolved and enlarged the scope of design including human-centred factors, such as social sustainability addresses design for quality of human life by considering transdisciplinary relationships with human diversity (Demirel & Duffy, 2013; Martin et al., 2013; Papetti et al., 2020). In this sense, for transitioning to sustainable manufacturing processes and consumption, human-centred factors play a core role in the achievement of sustainability-oriented operations throughout the supply chain (Bednar & Welch, 2020; Ceccacci et al., 2019; Grandi et al., 2020; Gualtieri et al., 2020; Lin, 2018; Rossi & Di Nicolantonio, 2020).

To address human-related roles in the context of Industry 4.0, Chart 1 shows a constantly growing interest in research and industrial practices where humans are placed at the centre of design across disciplines. The awareness of human roles in Industry 4.0 is increasing, as evidenced by active work in developing methods, exploring influencing factors, and proving the effectiveness of design oriented to humans. Examples of these designs include the avoidance of ergonomic risks (Caputo et al., 2019; Ceccacci et al., 2019), improvement of productivity and simultaneously biomechanical workloads (Gualtieri et al., 2020; Wojtynek et al., 2019), production performance in terms of quality and engineering time (Pacaux-Lemoine et al., 2017; Prinz et al., 2019).

CHART 1
Yearly publication trend on HCD in industry 4.0 (Chapter 3, Nguyen, Lasa, & Iriarte, 2022)



Besides, the scope of the research, which centers around humans, is extensive: customer-centric business models associated with customer involvement in design (Adrodegari & Saccani, 2020; Grieger & Ludwig, 2019; Saha et al., 2020; Santos et al., 2018); smart design engineering in which the users and emotional interactions are empowered (Benabdellah et al., 2019; Pereira Pessôa & Jauregui Becker, 2020); technology design in which users are centred (S. S.-C. Chen & Duh, 2019; Rogers et al., 2019); interaction designs among operators and smart manufacturing components (Klumpp et al., 2019; Rossi

& Di Nicolantonio, 2020); human- centred designs for product development (D. Chen et al., 2016; X. Wu et al., 2013); data processing by which humans remain the first design consideration of a data-driven approach (Crabtree & Mortier, 2015; Victorelli, Dos Reis, Santos, et al., 2020); sustainability in social-technical manufacturing contexts, including social robotic interactions with humans (Bednar & Welch, 2020; Leng & Jiang, 2017; Richert et al., 2018; Streitz, 2019).

However, numerous studies have been brought into existence but then disconnected from other studies. Specifically, the design concepts of HCD may not always be explicitly indicated by research papers, which may use various terms such as 'human' or 'user' and even consider them interchangeable. This confusion has also been reported by Holeman and Kane (2020) and Bazzano et al. (2017). Therefore, there is a need to understand and synthesize the different concepts of HCD across disciplines. Furthermore, several studies (R. Y. Chen, 2016; Mazali, 2018; Schulze et al., 2005; Witschel et al., 2019) have confirmed that involving stakeholders (such as users, customers, employees, suppliers, distributors, partners, regulators, etc.) throughout the life-cycle design process is essential for enhancing the credibility of information and promoting the sharing of transdisciplinary knowledge as valuable design inputs. Nevertheless, Richter et al. (2019) analyzed 42 existing design methodologies oriented to HCD and concluded that these methodologies did not fully address the roles of the actors and partners (stakeholders networks) and their engagement. As a consequence, these studies in industry and research alike are not regularly adopted, while the network of studies is scattered and diffused without forming any comprehensive structure.

Although numerous review papers portrayed, connected and synthesized the key developments regarding HCD over recent years, they focused on the reflection of emerging trends based on bibliometric results, debates, and priorities in their own research scope with their defined disciplines. Recently, Zarte et al. (2020) conducted SLR to structure design principles for HCD while Victorelli et al. (2020) provided an understanding of human-data integration with bibliometric analysis. Other representative review studies include Benabdellah et al. (2019), Duque et al. (2019), Kadir et al. (2019), Bazzano et al. (2017). These review studies do not pay attention to publications whose case studies contain a tremendous source of useful information. The results of a case study can have a very high impact on exploring in-depth conceptual testing and refinement associated with lessons learnt (Kadir et al., 2019; Tetnowski, 2015; Williams, 2011; Robert K. Yin, 2018), something that deserves to be treated as a special unit of analysis in the review process. Hence, case studies provide an opportunity to identify, deepen and synthesize the research outcomes of HCD through a cross-disciplinary lens.

Therefore, the thesis began with an extensive literature review (Chapter 3, Nguyen, Lasa, & Iriarte, 2022), which is a unique attempt to investigate the literature characteristics and lessons learned from a collection of 43 case studies on HCD in the context of Industry 4.0.

Human-centred design for product-service systems and advanced services

Our extensive literature review (Chapter 3, Nguyen, Lasa, & Iriarte, 2022) revealed that the research scope of HCD is extensive: human-robot collaboration (Fosch-Villaronga et al., 2020; Gervasi et al., 2020), human-in/on-the-loop (Kong et al., 2019; Vanderhaegen, 2019), human-machine interface (S. S.-C. Chen & Duh, 2019), user-centred design (Mazali, 2018), PSS (Bednar & Welch, 2020; Nguyen et al., 2021; Nguyen, Lasa, Iriarte, & Unamuno, 2022). Table 1 (Chapter 3, Nguyen, Lasa, & Iriarte, 2022) clearly shows that among the various human-oriented concepts, the trend of researching HCD in the context of PSS has gained the most attention, which led to this research focus on HCD for PSS. This is because PSS requires a human-centred design thinking process that not only generates the value-in-use to the customer through the identification of the latent requirements, but also manages the stakeholders and the technical feasibility (Cheah et al., 2019; Santos et al., 2018). The approach of HCD, such as service design, plays an important role in the design of service-oriented value propositions by providing a set of methods to improve customer experience and understand emerging social trends (Iriarte et al., 2018, 2023).

TABLE 1

Emerging trend of HCD concepts across case studies towards Industry 4.0 (Chapter 3)

Design concepts	2005-2007	2011-2013	2014-2016	2017-2020	Total cases
Human-centred design (HCD)	1	1	1	11	**14**
Product-service systems (PSS)	-	1	1	11	**13**
User-centred design (UCD)	-	-	1	7	**8**
Human-in/on-the-loop (HioTL)	-	-	-	3	**3**
Human-machine interface (HMI)	-	-	2	1	**3**
Human-robot collaboration (HRC)	-	-	-	2	**2**
Total cases	**1**	**2**	**5**	**35**	**43**

The research trend of PSS being discussed is a response to the challenge posed by the increasingly diverse range of products and customer expectations (Benabdellah et al., 2019; Chaudhuri et al., 2019; Fernandez-Carames & Fraga-Lamas, 2018; Pezzotta et al., 2018). This challenge has affected the development and manufacturing stages in different ways, necessitating new solutions that can enhance the customer's experience with the product throughout its life cycle. Various studies have addressed the challenge and identified the need for companies to gain new value creation through the extension of services by means of their PSS (Berkovich et al., 2014; Lerch & Gotsch, 2015; Orellano et al., 2017). This extension process known as servitization where PSS are often cited as the offering of a combination of products and services bundled together to enhance customer satisfaction across disciplines (Gaiardelli et al., 2021; Manzini & Vezzoli, 2003; Tan et al., 2009). In the automotive industry, Mahut et al. (2017) defined PSS as 'a new type of offer gathering products and service into an integrated bundle,' while in the context of data engineering, Berkovich et al. (2014) cited PSS as 'a bundle of hardware, software, and service components aimed at meeting the customer requirements as completely as possible.'. To generalize the PSS concept, Song (2017) considered PSS as 'a system of products and services that are not sold separately but offered as a result, or a functionality'. Above all, this thesis defined 'PSS as systems that represent bundles of products and services, enabling companies to create new value through the extension of services by means of their PSS'.

PSS are capable of fulfilling the customer’s present requirements while being adaptable to future needs and necessities through all their life-cycle stages (Cheah et al., 2019; Haber & Fargnoli, 2019; Leoni, 2019; Mourtzis et al., 2018; Pezzotta et al., 2018; Zhu et al., 2015). This is because PSS involve a novel strategy that emphasizes the delivery of value-in-use to customers (Baines & W. Lightfoot, 2014). This approach relies on the value proposition provided to the customer coming from the performance and utility of the product's usage, rather than the product alone (Tan et al., 2009). In this context, a value proposition is referred to as a statement that outlines the potential tangible and intangible benefits that a company believes it can create and align with the needs of its customers and also stakeholders (Lusch & Vargo, 2014). The value of proposition is determined by the degree of satisfaction and benefits that the customer receives from acquiring or consuming (i.e., value-in-exchange), and experiencing (i.e., value-in-use) bundles of products and services (PSS) (Gaiardelli et al., 2021). Hence, different variants of PSS will offer different value propositions perceived by the customer (Tukker, 2004).

In literature, considerable efforts have been made to categorize various types of PSS into distinct groups or classifications (Mathieu, 2001; Tukker, 2004): product-oriented groups (paying for buying pure products); use-oriented groups (paying for use); and result-oriented groups (paying for performance result). Lately, Baines & W. Lightfoot (2014) provided a delineation of use- and result-oriented groups as advanced services, which are a special case of PSS, that offer feature risk and revenue sharing agreements with customers over the life cycle of the service. Again, the idea of advanced services is to offer not only a product (by ownership), but also its performance (e.g., pay-per-performance) and usage (e.g., pay-per-use) as a bundle of products and services (Zheng et al., 2019; Ziaee Bigdeli et al., 2018), enabling companies' value chains to be extended. Advanced services offer new value creation by focusing on the delivery of product-service performance outcomes in terms of use-based and/or result-based contracts (Baines et al., 2013; Calabrese et al., 2021; Nguyen, Lasa, Iriarte, & Unamuno, 2022). These contracts allow a customer to pay based on a result, output, performance and/ or outcome of product-service delivery. Some typical cases of such contracts include the 'power-by-the-hour' model in terms of which Rolls-Royce receives a fixed price for each hour their engines work for customers (Smith, 2013), and the 'pay-per-lux' model where the customer buys a subscription from Philips for a certain amount of light per year instead of buying Philips' lamps (Salwin et al., 2018).

Industry 4.0 technologies, including machine learning (Jingchen Cong et al., 2022), the Internet of Things (IoT), big data, and cloud computing (Gaiardelli et al., 2021), have emerged as key enablers of advanced services, which are shaped by the alignment between service-product-technology solutions and market development (Chew, 2016; Zheng et al., 2019). By leveraging Industry 4.0 technologies, companies can unlock the full potential of advanced services (Ghezzi & Cavallo, 2020), reflecting new ways of value creation in diverse aspects (Calabrese et al., 2021; Jia et al., 2021; Lee et al., 2019; Li et al., 2021; Nguyen, Lasa, Iriarte, & Unamuno, 2022): smart connected products and services (smart PSS), commercial gains (e.g., revenue growth through hybrid offerings), and compelling sustainability (e.g., efficiency in material and energy usage).

However, Jovanovic et al. (2022) argue that scholars often rely on technologies and data to create advanced services and overlook the importance of co-creation processes driven by the company. Kohtamäki & Partanen (2016) highlight the benefits of co-creation in advanced services, particularly in terms of profitability. To create advanced services, companies should take into account their customers' value creation activities, such as processes, competencies, and requirements, both tangible and intangible (Kindström, 2010). As a result, companies need to adopt a co-creation mindset and interact with customers and other stakeholders as a human-centred approach, equipped with appropriate design methodologies, approaches, and methods to design advanced services (Kamalaldin et al., 2020).

Research motivation

To design for these advanced services, a structural methodology is required to reflect the life-cycle service design, central roles of human actors and then enable effective service delivery (Kwon et al., 2021; Lee et al., 2019). The design methodology requires human actors to be placed in the center of design work (Korper et al., 2020), allowing for capturing customer latent needs and understanding stakeholder requirements (Santos et al., 2018). To realize this, HCD—that is a set of design principles, methods and tools and also a philosophy—enables design practitioners to co-create value propositions with people (or stakeholders) across the life-cycle design process (Costa et al., 2018; Lofthouse & Prendeville, 2018; Sierra-Pérez et al., 2021). Nevertheless, previous reviews have revealed that human factors are not often addressed, even though the design for advanced services requires human-centred thinking (Solem et al., 2021; Zheng et al., 2019). Specifically, Chapter 3 presented the detailed analysis of 43 case studies in HCD and PSS in Industry 4.0; only 12 % of these studies made an effort to validate and confirm the important inclusions of human factors—background, age, gender, education, cultural influences, and privacy management—in design. The human-centric approach in design was also recently emphasized by Piera et al. (2022) who called for the digitalization of new smart services (e.g., artificial intelligent supporting services) by accommodating social-technical factors: aging, disabilities, inexperience, conform and wellbeing. Above all, design for advanced services demands a new HCD methodology to design new value propositions. This demand establishes the scope of the present thesis, conceptually shaping the development of a new design methodology oriented to HCD for advanced services.

In addition, even though researchers have conceptualized different design methodologies for advanced services, these methodologies are limited to partially addressing one or some key design elements, e.g., life-cycle service design, or involvement of stakeholder networks. Specifically, Agher et al. (2021), Zheng et al. (2019) revealed that one of the first key design elements is the life-cycle service design, which is often missed in existing design methodologies that have been limited to the concept development stage. Besides, Richter et al. (2019) shows clearly that existing design approaches did not fully consider stakeholder networks and their roles, although they play a vital role in value co-creation as a key design element. A lack of consideration of these key design elements could cause confusion in practice, resulting in an ineffective implementation leading to a “service paradox” (Kwon et al., 2021; Ping et al., 2020). Here, the service paradox reflects a situation in which servitized manufacturing does not succeed in developing a profitable service business to complement an existing product business (Cheah et al., 2019; Kowalkowski et al., 2017; Valtakoski, 2017). Therefore, the design for advanced services poses requirements for a new design methodology that is not only oriented to HCD, but also encapsulates the must-have relationship among these key design elements. These key design elements need to be methodically addressed in a new design methodology to develop effective advanced service design.

Therefore, to advance the body of research, this thesis aims to address the issues above by developing a new structural HCD methodology, called DIMAND for short, for advanced service design. This new methodology systematically encapsulates the key design elements and their relations into account, making the design of advanced services more practical.

1.2. Overall objective and research questions

In the light of the above, the thesis aims to formulate design knowledge through the development of a new HCD methodology that expresses the relations of key design elements within the domain of advanced service design. In order to realize the aim, there are two following research questions that need to be fulfilled:

RQ1: What are the key design elements of an effective HCD methodology for advanced services?

A proper design methodology for advanced services needs to take key design elements into account for effective implementation in practice (Kwon et al., 2021; Lee et al., 2019). Some researchers have conceptualized different design methodologies for advanced services; they acknowledged that these methodologies are limited to partially addressing one or some key design elements, leading to confusion in practice (Kwon et al., 2021; Ping et al., 2020). Specifically, Marilungo et al. (2016) and Vasantha et al. (2012) analyzed different design methodologies (e.g., design for PSS, service engineering) in detail and then drew the conclusion that some design phases (e.g., planning and design) were well addressed; however, others (e.g., implementation, monitoring, feedbacks among phases) were vaguely defined. Such design methodologies overlook the whole design phases, resulting in decreased effectiveness in practical use. Furthermore, Richter et al. (2019) analyzed 42 existing design methodologies for PSS; they concluded that such methodologies did not fully address roles of actors and partners at different life-cycle design phases, leading to ineffective design for PSS' stakeholder requirements.

Even though some studies have defined design methodologies, they partially covered one or some key design elements for advanced services, which can cause confusion in practice. Therefore, there is a need to answer RQ1 or the key design elements (e.g., life-cycle service design, or involvement of stakeholder networks) of an effective HCD methodology for advanced services need to be identified. Once the key design elements are defined, they and their relations must be addressed in a new HCD methodology to develop effective advanced service design. This leads to the second research question.

RQ2: How are the identified key design elements and their relations incorporated in a single-view structure in accordance with a human-centric approach?

The answer for this second research question (RQ2) fulfills the thesis aim of developing a new design methodology incorporating the key design elements and their relations, identified from RQ1, in a single-view structure in accordance with a human-centric approach. RQ2 was motivated by the mentioned research gap above in which existing methodologies did not fully comprehend—or just partially covered—the key design elements for advanced service design, causing decreased effectiveness in practical use.

Therefore, on the opposite end of existing intuitive approaches, the thesis aims to answer RQ2 for the development of a new HCD methodology that helps design teams govern the entire life-cycle service design by simultaneously considering the key design elements and their relations, hence making the design of advanced services more practical.

1.3. Structure and research process

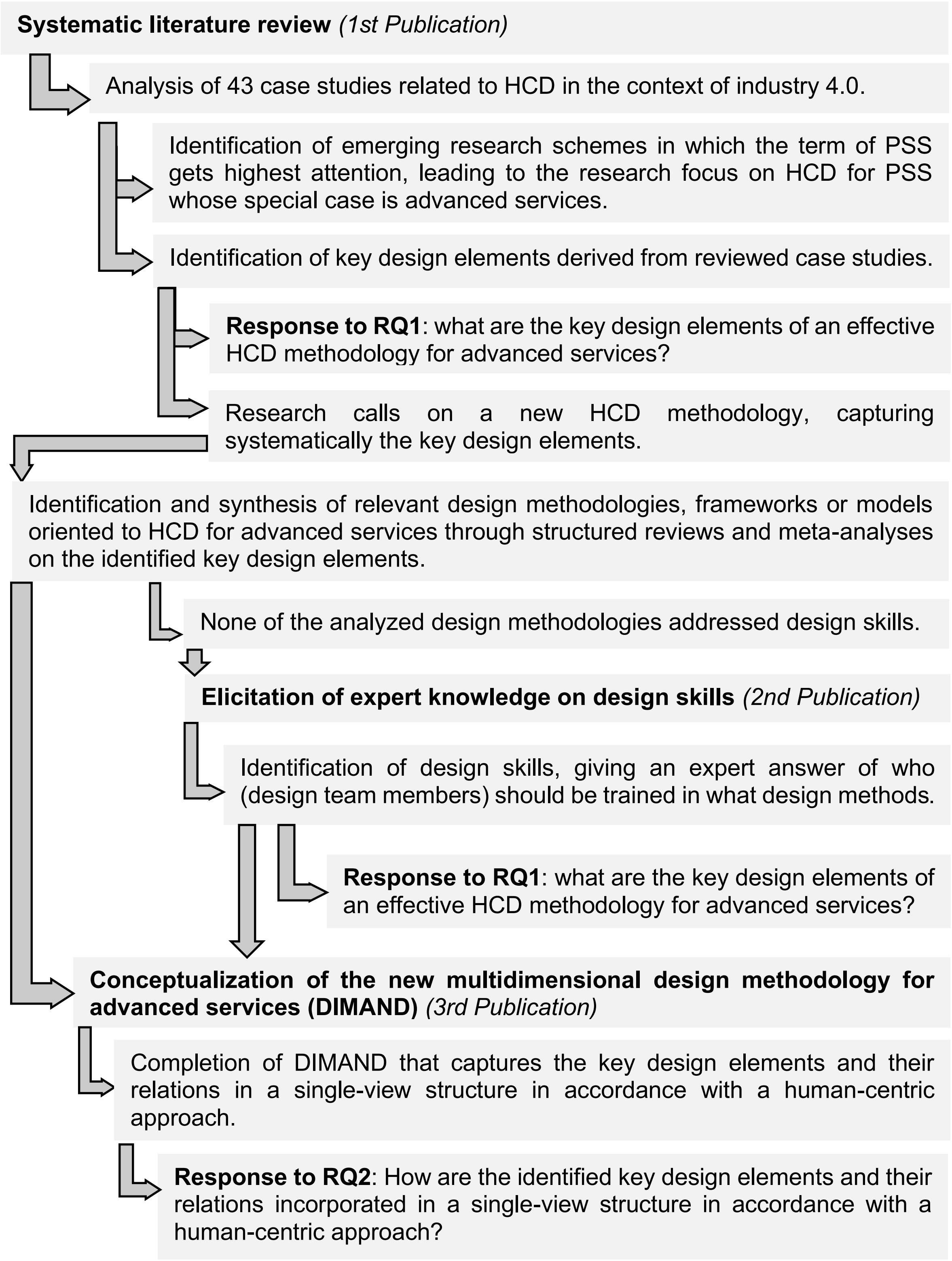
The pursuit of the two research questions above (RQ1 and RQ2) resulted in three main publications. Figure 1 illustrates the logical flow between the three publications, demonstrating how each research question is examined by the corresponding publications whose detailed contributions are presented in Chapter 2.

Chapter 3 (Nguyen, Lasa, & Iriarte, 2022) presents a unique attempt to examine the characteristics of literature and the lessons learned from a collection of 43 case studies on human-centred design (HCD) in the context of Industry 4.0. The study highlights various human-oriented concepts, such as human-robot collaboration, human-in/on-the-loop, human-machine interface, user-centred design, and PSS. Through the extensive literature review, we found that the research trend on PSS has garnered the most attention (Table 1), which led to this research focus on HCD for PSS whose special case is advanced services. Moreover, the first research question (RQ1) came out and was partially answered by the identification of the key design elements. Based on identified research gaps derived from literature review, the study proposed future research that calls for a new HCD methodology that captures the key design elements; this call leads to RQ2.

To answer RQ1, an analysis of the most recent literature reviews related to design for advanced services has revealed that none of the analyzed design methodologies addressed design skills while these design skills are important because they affect key performance indicators in design work. Therefore, Chapter 4 (Nguyen, Lasa, Iriarte, Atxa, et al., 2022a) contributed to the body of knowledge by answering what service design skills are important for design team members (internal stakeholders) with the help of experts in the field.

At this stage, the key design elements above are defined and ready to be assembled in the new multidimensional design methodology (DIMAND) for advanced services in a single-view structure in accordance with a human-centric approach. How to build DIMAND is also the second research question (RQ2); this is answered by Chapter 5 (Nguyen, Lasa, Iriarte, Atxa, et al., 2022b).

The rest of the thesis includes Chapter 2 that summarizes the research contributions and highlights derived from the publications to fulfill the research questions accordingly. Subsequently, the next three consecutive chapters (Chapter 3, Chapter 4, Chapter 5) enclose the full content of corresponding publications in order. Lastly, the sixth chapter expounds the principal theoretical contributions and practical contributions to both designers and engineers. The research limitations and future research agenda are also outlined.



Systematic literature review *(1st Publication)*

Analysis of 43 case studies related to HCD in the context of industry 4.0.

Identification of emerging research schemes in which the term of PSS gets highest attention, leading to the research focus on HCD for PSS whose special case is advanced services.

Identification of key design elements derived from reviewed case studies.

Response to RQ1: what are the key design elements of an effective HCD methodology for advanced services?

Research calls on a new HCD methodology, capturing systematically the key design elements.

Identification and synthesis of relevant design methodologies, frameworks or models oriented to HCD for advanced services through structured reviews and meta-analyses on the identified key design elements.

None of the analyzed design methodologies addressed design skills.

Elicitation of expert knowledge on design skills *(2nd Publication)*

Identification of design skills, giving an expert answer of who (design team members) should be trained in what design methods.

Response to RQ1: what are the key design elements of an effective HCD methodology for advanced services?

Conceptualization of the new multidimensional design methodology for advanced services (DIMAND) *(3rd Publication)*

Completion of DIMAND that captures the key design elements and their relations in a single-view structure in accordance with a human-centric approach.

Response to RQ2: How are the identified key design elements and their relations incorporated in a single-view structure in accordance with a human-centric approach?

FIGURE 1
The logic of the thesis

CHAPTER 2

Contributions and highlights

2. Contributions and highlights

This chapter highlights the key findings of the three publications, which are presented in the order of their respective research questions, as illustrated in Figure 1. The complete content and contributions of these publications are presented in Chapters 3, 4, and 5, respectively.

2.1. Identification of key design elements

Research context

Chapter 3 is a unique attempt to investigate the literature characteristics and lessons learnt derived from a collection of 43 case studies regarding HCD in the context of Industry 4.0. This attempt is completed by a well-rounded systematic literature review whose special unit of analysis is given to the case studies. The review objective is to make contributions to the future research agenda by harmonizing the lessons learnt that reveal the research results and limitations of the case studies. The significance of case studies lies in the abundance of valuable information they provide, which can greatly aid in exploring in-depth conceptual testing and refinement associated with lessons learnt (Kadir et al., 2019; R. K. Yin, 2018). Therefore, the present study (Chapter 3) took a unique approach by analyzing case studies in the review process, which distinguishes it from existing review studies (Victorelli, Dos Reis, Hornung, et al., 2020; Zarte et al., 2020) that rely on bibliometric analysis.

As a result, a thorough examination of 43 case studies revealed that the research scope of HCD is broadened in the context of Industry 4.0 in which HCD is based for various design fields: PSS, user-centred design, human-in/on-the-loop, human-machine interface, and human-robot collaboration. Among the various human-oriented concepts, Table 1 clearly shows that the trend of researching HCD in the context of PSS has gained the most attention, which led to this research focus on HCD for PSS whose special case is advanced services. Advanced services offer new value creation by focusing on the delivery of product-service performance outcomes in terms of use-based and/or result-based contracts (Baines et al., 2013; Calabrese et al., 2021; Nguyen, Lasa, Iriarte, & Unamuno, 2022).

To design for advanced services, HCD needs to be considered to help design practitioners in focusing on human factors and diversity to gain critical design requirements and feedback. These design requirements may range from human use and performance (e.g., postural comfort, physical ergonomics) (Caputo et al., 2019; Peruzzini et al., 2019) to human perception and cognition (e.g., emotional stress, conscientiousness) (Richert et al., 2018; L. Wu et al., 2016). For instance, Sierra-Pérez et al. (2021) applied HCD to capture the stakeholder requirements in both functional requirements (e.g., scooter battery levels, scooter travel time) and non-functional requirements (e.g., trustworthiness, usefulness) for service design. Similarly, Bu et al. (2021) and Chang et al. (2019) placed people (users and stakeholders) at the center of the requirements in their design approaches for user-centric smart PSS (smart connected products and services). To confirm the role of HCD, Zheng et al. (2019) systematically reviewed 97 studies and relevant works related to smart PSS before coming to the conclusion that a human-centric approach must be addressed in a new design methodology. Therefore, a design methodology for advanced services must be oriented to HCD.

Moreover, a proper design methodology for advanced services needs to take key design elements into account for effective implementation in practice (Kwon et al., 2021; Lee et al., 2019). Some researchers have conceptualized different design methodologies for advanced services; they acknowledged that these methodologies are limited to partially addressing one or some key design elements, leading to confusion in practice (Kwon et al., 2021; Ping et al., 2020). For instance, of the 43 case studies analyzed in-depth, Zhu et al. (2015) conducted a case study of a PSS for an aircraft engine. The study reported that customer requirements, where the customer is an external stakeholder in the *stakeholder network*, must be considered during the design phase (*the life-cycle service design*) for the design to be successful.

As a result, to identify systematically the key design elements, the examination of 43 case studies led to the discovery that the most significant finding (22 out of 43 case studies) was related to the identification of key design elements regarded as design success factors. These factors shed light on how successful HCD can be applied in different settings, particularly in the context of advanced services. Figure 2 structures those success factors as a triangular decision-making diagram.

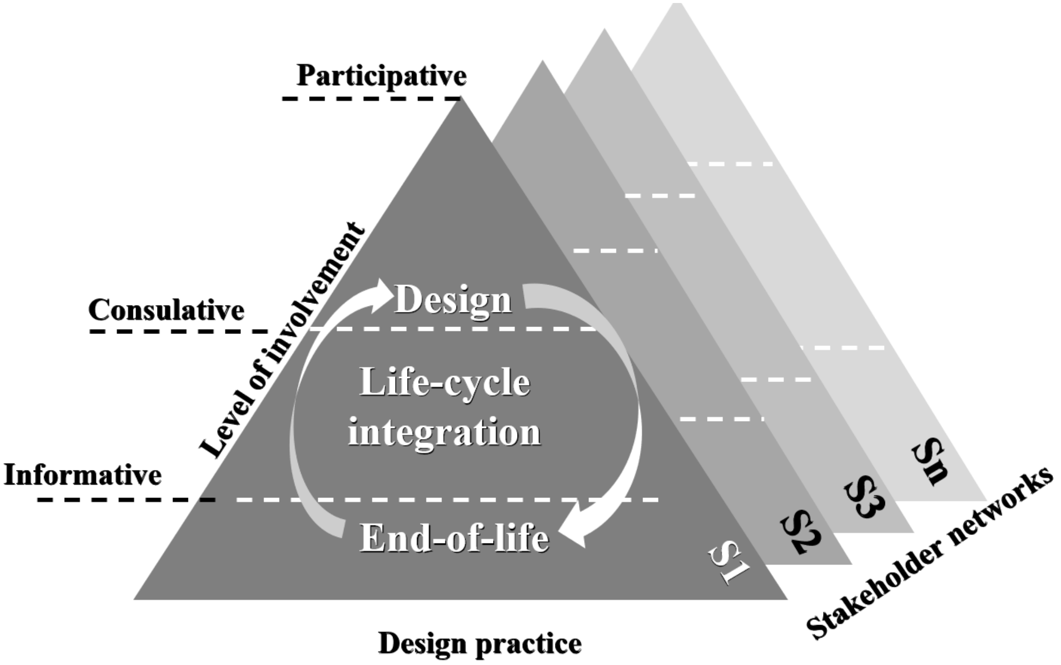


FIGURE 2

The design success factors in HCD reflect design decisions on who in the stakeholder networks (S1, S2, S3, Sn) will be involved, at what levels of involvement, where the involvement will take place in each life-cycle design phase, and what design practice should be exploited (Chapter 3)

Key findings

Life cycle service design

The life-cycle integration encompasses all life-cycle (service) design phases in which design processes (e.g., design requirements elicitation, prototyping) are defined to execute their corresponding phases (Marilungo et al., 2016; Vasantha et al., 2012; Woitsch et al., 2022): planning and design, implementation and monitoring, product/service usage, and feedback loops between phases. This life-cycle perspective aims to manage design activities of products and/or services across their life cycle, towards sustainability. For instance, life-cycle cost analysis for economics is an aspect of this perspective (Aurich et al., 2007; Jasiulewicz-Kaczmarek et al., 2021; Kambanou, 2020). In an empirical study, Dimitris Mourtzis et al. (2018) designed a method for quantifying PSS customization complexity in which a company provides advanced services of remote health monitoring and machine data analytics for increased product quality and performance optimization. They concluded that by monitoring PSS throughout the life-cycle service design, companies can maintain their competitiveness and sustainability.

Therefore, the first class of the key design elements is the life-cycle service design, which needs to be expressed properly in a proper design methodology for advanced services to cover the life-cycle design phases associated with design processes.

Stakeholder networks

Second, the organizational, social, and environmental contexts—which involve stakeholders (e.g., users, customers, employees, suppliers, distributors, partners, regulators, etc.) through the life-cycle design phases—are essential for enhancing the credibility of information and promoting the sharing of transdisciplinary knowledge as valuable design inputs (R. Y. Chen, 2016; Mazali, 2018; Schulze et al., 2005; Witschel et al., 2019). The diversity in interests and expectations of the stakeholders needs to be respected and analyzed to comprehend the impact of stakeholder interactions and their features at different life-cycle design phases (Dimitris Mourtzis et al., 2018; Turetken et al., 2019; Zhang et al., 2020). Another finding is the engagement modes of stakeholders, which are depicted by three levels of stakeholder involvement: : (i) an informative level, in which stakeholders only provide and receive design information; (ii) a consultative level, in which they comment on predefined design scenarios; and (iii) a participative level, in which they make influencing decisions on a design process and outcome (Schulze et al., 2005; van Lopik et al., 2020).

Thus, to develop effective advanced service design, a design methodology must cover this second class of key design elements: stakeholder networks that address both internal and external stakeholders, and their involvement in different life-cycle design phases.

Design practice (new service development methods)

Third, design practice that refers to the design methods used for the design development—which responds to the extent to which the data about users, customers, and other relevant stakeholders should be properly obtained and analyzed—needs to be defined. These data include physical activities, behaviors, opinions, feelings, personalities, and physiological responses (Lin, 2018; Peruzzini et al., 2019; Richert et al., 2018; W. Wang et al., 2018). Therefore, to carry out the design development, proper design methods need to be defined. For instance, on one hand, non-engineering design methods (e.g., participatory design, interviews) can help designers focus on human diversity to gain critical design requirements: requirements elicitation acquired from maintenance professionals by field studies (Kaasinen et al., 2018), human perception of different stakeholders by focus groups (Turetken et al., 2019) and usage difficulties of non-expert users by scenario observation (J. W. Song et al., 2016). On the other hand, the engineering design methods (e.g., Kano model, quality function deployment) enrich the prioritization and segmentation of these design requirements (Haber & Fargnoli, 2019; Ping et al., 2020).

Accordingly, a design methodology for advanced services must incorporate the new set of design methods that cover both engineering and non-engineering design methods, this new set of design methods is called the new service development methods that support design activities across different life-cycle design phases.

Conclusion

Based on the in-depth review of case studies, Figure 2 captures the most significant finding that gives an answer to the first research question above (RQ1): What are the key design elements of an effective HCD methodology for advanced services?. The design success factors reflect the proper consideration of key design elements in design: (i) life-cycle service design (life-cycle integration), (ii) stakeholder networks, (iii) new service development methods (design practice).

Next research contributions

However, the most recent literature reviews revealed that the key design elements were not always addressed in existing design methodologies for advanced services, leading to confusion in practice (Kwon et al., 2021; Ping et al., 2020). First, on the key design element of life-cycler service design, Marilungo et al. (2016) and Vasantha et al. (2012) analyzed different design approaches (e.g., design for PSS, service engineering) in detail. They drew the conclusion that some design phases (e.g., planning and design) were well addressed; however, others (e.g., implementation, monitoring, feedback among phases) were vaguely defined. Agreeing with this conclusion, Agher et al. (2021) and Song and Sakao (2017) also carried out extensive review works before concluding that there is a lack of systematic methodical support covering the entire life-cycle service design.

Second, Richter et al. (2019) analyzed 42 existing design methodologies for PSS, concluding that these methodologies did not fully address the key design element: the actors and partners (stakeholders networks) and their engagement. Third, Jing-chen Cong et al. (2020) carried out a systematic review of the design approaches since the coining of the term PSS to May, 2020, highlighting limitations in studies focusing on adopting the engineering design methods—such as TRIZ as creative problem-solving techniques (Lee et al., 2019), quality function deployment (Ping et al., 2020) or Kansei engineering (D. Chang et al., 2019)—instead of new service development methods.

Identification of design skills

Besides, the review work of Richter et al. (2019) stated that the existing methodologies did not fully address the design skills required for design practitioners, who are typically internal stakeholders (e.g., designers, engineers, manufacturing and maintenance staff) and responsible for design activities and outcomes. This conclusion is inline with our review work (Chapter 3) where none of the analyzed case studies addressed design skills in any detail levels. Here, design skills are defined as the ability of an actor who practices particular new service development methods to perform design activities (e.g., market research, design for agile prototyping). The consideration of design skills in a design methodology is required, as indicated by Baines et al. (2013) and Ingo Oswald Karpen et al. (2017), who demonstrated that design skills are the key factors influencing key performance in advanced service design. Agreeing with this point, Spreitzer et al. (2012) requested that company staff (internal stakeholders) need to be equipped with the proper skills to enable them to understand how their work performance is carried out and developed. Thus, training on these proper skills helps companies enhance their sustainable development. This also means that the importance of anyone directly or indirectly involved in the making of products and/or services is embraced, hence developing a business culture on advanced service design instead of only market orientation (Fernandes et al., 2019; Gilles & Christine, 2016).

Therefore, it is necessary to address the design skills that serve as the key design element. This leads to the next research contribution, the identification of design skills required for advanced service design. At this stage, the identification of design skills answers RQ1 (Figure 1), as summarized in Section 2.2 and detailed in Chapter 4.

Conceptualization of a new multidimensional design methodology for advanced services (DIMAND)

As mentioned above, even though some studies have defined design methodologies, they partially covered one or some key design elements for advanced services, which can cause an ineffective implementation leading to a “service paradox” (Kwon et al., 2021; Ping et al., 2020). Hence, this calls for a new HCD methodology that incorporates the key design elements, leading to the second research question (RQ2, Figure 1): How are the identified key design elements and their relations incorporated in a single-view structure in accordance with a human-centric approach?

To respond to the call, the next contribution of the present thesis (Chapter 5) aims to conceptually propose a multidimensional design methodology (DIMAND) that captures the key design elements that must be addressed to develop effective advanced service design. Specifically, DIMAND encapsulates the key design elements—(i) life-cycle service design, (ii) stakeholder networks, (iii) new service development methods, and (iv) design skills—and their relations in a single-view structure in accordance with a human-centric approach.

Hence, DIMAND offers a novel and holistic guideline for design practitioners and engineers to obtain coherence in all the life-cycle design processes by simultaneously taking these key design elements and their relations into account, making the design of advanced services more practical. This contribution is summarized in Section 2.2 and presented fully in Chapter 5.

2.2. Identification of design skills as a key design element

Research context

In addition to the key design elements (life-cycle service design, stakeholder networks, new service development methods), Chapter 4 made the contribution of defining design skills that serve as the key design element of advanced service design, which addresses RQ1: What are the key design elements of an effective HCD methodology for advanced services?.

To design for advanced services, it is key to provide the design team members (design practitioners) or internal stakeholders of a company with the necessary design skills (e.g., skills in market research or prototyping). This is important because design skills affect the key performance indicators in design work (Baines et al., 2013; Karpen et al., 2017) and help designers to understand their short-term functioning and long-term work development, enhancing the sustainable development of a company (Spreitzer et al., 2012). Therefore, by receiving training in these relevant skills, a company can improve their design ability to sustainably grow. This, in turn, acknowledges the significance of all individuals who contribute to the creation of advanced services, leading to the development of a company culture focused on advanced service design rather than solely market-driven objectives (Fernandes et al., 2019; Gilles & Christine, 2016).

However, the review by Richter et al. (2019) notes that existing design methodologies do not address the design skills required for design practitioners, who are typically internal stakeholders (e.g., designers, engineers, manufacturing, and maintenance personnel) responsible for design activities and outcomes. Consistent with this finding, our comprehensive review (Chapter 3) also confirmed that the case studies examined overlook the design skills. Therefore, Chapter 4 contributed into the body of knowledge by answering what service design skills are important for design team members (internal stakeholders) by answering this following primary research question in the present study (Chapter 4):

- Who (design team members, e.g., an engineer, a financial analyst, a marketer) needs to know and/or practice what design methods (e.g., interview techniques, prototyping) as design skills, to perform one or more design activities (e.g., to understand the customer's latent needs, or to use wireframes for prototyping)?

The answer to this primary research question will also help design practitioners to build internal service capability ('who needs to be trained in what') and make decisions on training priorities in terms of their business resource constraints. Therefore, there are the following two secondary research questions in the present study (Chapter 4):

- Who should be trained in what design methods?
- How can these design methods be prioritized in building service capability (training and skills enhancement)?

The answers to the research questions can be varied, as they depend on the use context (e.g., company size, design knowledge and experience) and the perspective of the person answering the questions, leading to an unstructured decision problem. To tackle this problem, experts are in the best position to provide answers based on their expertise from both academic and industrial perspectives (R.R. Hoffman et al., 2008; Robert R. Hoffman et al., 1995). Therefore, the study conducted an expert survey of 10 experts from which a dataset was developed and analyzed by the method of analytical hierarchy process (AHP) to elicit expert knowledge related to the field of advanced service design in order to answer the research questions. This full research methodology and data analysis is detailed in Chapter 4.

The expert dataset whose analysis result is summarized in Table 2 aims to enable design practitioners to determine which service design skills are valued for design teams from the perspective of service design experts, enabling practitioners to build service capability.

Key findings

Table 2 directly answers the research questions related to the identification of design skills. Specifically, for the primary research question, the ‘designers’ and ‘engineers and/or technicians’ preferably need to master the skill set of ‘idea exploration’ better than the other groups of design team members in terms of the aggregated perspectives of all surveyed experts.

TABLE 2
Matrix of design skills (Chapter 4)

	Design team members / design practitioners / internal stakeholders[a]				
Group of design methods	Executive officers	Marketing analysts	Finance analysts	Engineers and/or technicians	Designers
Idea exploration				S	S
Participatory design		S		S	S
CX-centred methods		S			S
Idea clustering		S			S
Prototyping methods				S	S
Operations-centred methods				S	S
Business analytics	S		S		
Engineering methods				S	S
Evaluation methods		S			S

[a]S represents a corresponding skill set that is prioritized for training to the corresponding design team members. For instance, the design team members of engineers and/or technicians and designers are prioritized to acquire the skill set of idea exploration. The same explanation is applicable to the rest of design methods

Similarly, the answers to the two secondary research questions—(i) who should be trained in what design methods, and (ii) how can these design methods be prioritized in building service capability—are also based on the “S” in Table 2. For instance, in the skill set of ‘participatory design’, the ‘designers’, ‘marketing analysts’, and ‘engineers and/or technicians’ should be prioritized for the training of the skill set in the same order. As can be seen in Table 2, the skills of ‘designers’ are in the highest demand, except for the skill set of ‘business analytics’ (e.g., game theory, profit formula), which should be represented to a greater extent by ‘executive officers and ‘financial analysts’. In addition to designers, ‘engineers’ should not only be competent in technical skills (‘prototyping methods’, ‘operations-centred methods’ and ‘engineering methods’). They should preferably be trained to know the skill sets of ‘idea exploration’ and ‘participatory design’ used to understand both the tangible and latent requirements of customers.

Conclusion

Above all, Table 2 addresses the research questions related to the identification of design skills and enables design practitioners to build a transdisciplinary design team in which each group of design methods can be handled by two or three job roles, in the order of priority. By building the transdisciplinary design team, the skills and mindset from different fields (e.g., service, engineering and industrial design) can function as an accelerator for the design of advanced services to the market by combining technological design and HCD (Acklin, 2010). Among the design teams, except for the skill set of “business analytics” (e.g., game theory, contingency theory), “designers” are required to practice all skill sets. In line with this result, Calabretta, G. and De Lille (2016) suggested a much broader role for design professionals in the company to enable the transition process towards the effective design of advanced services.

In addition to designers, the roles of “engineers and/or technicians” and “marketing analysts” were also emphasized. The engineers—who may come from different departments, such as research and development, manufacturing and maintenance, and quality assurance—should not only be qualified in technical skills, including “prototyping methods”, “operations-centred methods”, and “engineering methods”. But they should also understand what customers want in both the functional (e.g., technical problems, service quality reports) and non-functional requirements (e.g., user perception, cognitive and work domain). Comprehending customer requirements can be more effective by training the skill sets of “idea exploration” (e.g., focus-group and interview techniques) and “participatory design” (e.g., service design labs and workshops) for both engineers and marketing analysts. Coreynen et al. (2018) also stated that front-office staff need to master service skill sets beyond their professional skills to support in upscaling or in the successful adoption for the design of advanced services.

Next research contribution

Above all, Chapter 4 made the contribution in literature through the identification of design skills and then addresses RQ1 (Figure 1). This leads to the full identification of four key design elements: (i) life-cycle service design, (ii) stakeholder networks, (iii) new service development methods, and (iv) design skills.

At this stage, the identified key design elements are ready to be compiled into a single-view structure that follows a human-centric approach, in order to conceptualize a new multidimensional design methodology for advanced services (DIMAND), which addresses RQ2 (Figure 1): How are the identified key design elements and their relations incorporated in a single-view structure in accordance with a human-centric approach?. This contribution is summarized in the following section and presented by Chapter 5 in detail.

2.3. Conceptualization of the new multidimensional design methodology for advanced services (DIMAND)

Research context

Industries and academics have shown interest in advanced services as a means to explore new ways of creating customer value propositions (J. Wang et al., 2022). In order to create such advanced services, it is necessary to adopt a structured methodology that takes into account the key design elements and their relations, as shown in Figure 3.

Life-cycle service design

First, the design methodology needs to incorporate the entire *life cycle service design* and ensure effective service delivery, as noted by Kwon et al. (2021) and C.-H. Lee et al. (2019). Life-cycle service design must cover all life-cycle design phases in which design processes are defined to execute their corresponding phases (Marilungo et al., 2016; Vasantha et al., 2012; Woitsch et al., 2022): the *diagnose* and *identify* phase (planning), the *measure* and *analyze* phase (design), the *navigate* phase (implementation and monitoring), and the *delivery* phase (product/service usage). However, not existing design methodologies fully proposed life-cycle design phases and processes.

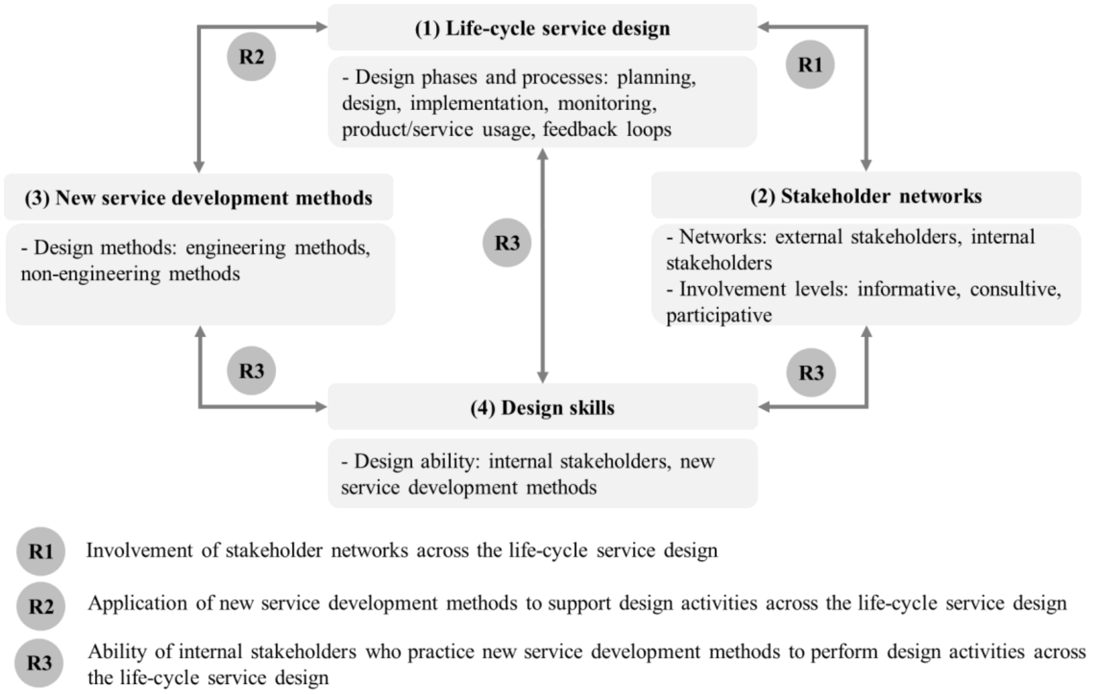


FIGURE 3
Formalization of the key design elements and their relations for advanced service design

Specifically, Acklin (2010) and Iriarte et al. (2018) paid attention to the *diagnose* and *identify* phase. On one hand, Acklin (2010) proposed a design methodology whose first design process was to analyze the business context for the acquisition of background knowledge for design: to understand what a company has learned so far and its business ecosystem (e.g., markets, customer trends). This understanding can enable the company to design for service strategy (e.g., communication and brand strategies). On the other hand, Iriarte et al. (2018) highlighted their design methodology whose starting design process was to analyze the business context by taking a snapshot of a detailed investigation of the business: competitive advantages and potential value propositions for advanced services in the machinery industry. According to the authors, this investigation can help the company properly identify stakeholder networks: key customer staff responsible for the purchase of the solution on offer (e.g., top managers, technicians, and operations personnel), and internal stakeholders (e.g., quality manager, operations manager, product manager, technicians).

Instead of focusing on the *diagnose* and *identify* phase, Yu (2018) focused only on the *measure* and *analyze* phase. The author proposed a HCD methodology whose starting design task was to measure stakeholder needs in both functional and non-functional requirements of students in terms of a library service (e.g., experiences, opinions, user perception). Subsequently, the measured requirements were the design inputs used to analyze the value propositions according to user contexts, such as physical conditions, technical capabilities, and cognitive links among product attributes, consequences, and goals.

Therefore, the first class of key design elements is the life-cycle service design (Figure 3), which needs to be expressed in a new design methodology to synthesize and cover the life-cycle design phases associated with design processes.

Stakeholder networks

Second, a design methodology also requires the involvement of *stakeholder networks* in the design process, as highlighted by Korper et al. (2020), which helps to identify and fulfill the latent needs of customers, as well as meet the requirements of stakeholders, as discussed by Santos et al. (2018). Our extensive review (Figure 2) also shows that stakeholder networks must consider both internal and external stakeholder networks, and their involvement levels—an informative level, a consultative level, a participative level—across the life-cycle service design. But not all design approaches address fully the stakeholder networks and their involvement.

Particularly, Chew (2016) who highlighted the importance of finance analysts whose *consulting* roles were to cooperate with other design teams (e.g., market analysts and IT technicians). This cooperation was intended to design for service strategy (e.g., business and market models)—and measure stakeholder needs, verify the measured needs, analyze the value propositions and formulate the service concept. Moreover, Chew (2016) also appreciated the *participative* role of finance analysts required to design for service system architecture in terms of the monetization process linked to the business strategy. Although Iriarte et al. (2018) did not discuss the role of finance analysts in the design team, they explicitly highlighted the *participative* involvement of executive officers across departments (e.g., business managers, project managers, sales managers) to analyze the business context in the *diagnose* phase. They also underlined the *participative* roles of researchers who offered their design knowledge to facilitate their case company to analyze the business context and other design processes.

Instead of highlighting an individual role, cooperation among design teams has also been noted as essential, as emphasized by Papazoglou et al. (2020). Specifically, marketing analysts, designers and engineers—who are responsible for manufacturing and maintenance—work *participatively* together with external stakeholders (e.g., customers, third-party suppliers) to verify whether or not customer needs can be fulfilled with the company capability (e.g., product-service design, production scheduling and capability, commissioning).

Above all, a new design methodology for advanced services is required to incorporate the complete piece of information about stakeholder networks regarded as the second class of key design elements. This offers a complete guideline on how to oversee and plan who will do what across the life-cycle service design. This relation between the stakeholder networks and life-cycle service design is labeled as R1 in Figure 3.

New service development methods

Third, when designing advanced services, it's not enough to solely rely on engineering methods like TRIZ, quality function deployment, or Kansei engineering (Lee et al., 2019; Ping et al., 2020). Instead, it's crucial to encompass both engineering and non-engineering methods such as interviews, focus groups, and customer journey maps to ensure that all aspects of advanced service design are adequately captured. However, existing design methodologies do not always fulfill the requirement.

Jing-chen Cong et al. (2020) discovered that design approaches for PSS were limited to engineering methods such as TRIZ, quality function deployment, or Kansei engineering instead of new service development methods from the coining of the term PSS to May 2020. This is consistent with the results of our extensive review (Chapter 3) which emphasized the significance of both engineering and non-engineering methods across the life-cycle service design (Figure 2). These methods are required for advanced service design, taking into account physical, cognitive, and social factors. Incorporating non-engineering methods such as participatory design and interviews helps designers concentrate on human diversity, leading to crucial design requirements in the *measure* phase. Engineering methods, on the other hand, such as quality function deployment (Ping et al., 2020), enhance the prioritization and segmentation of these design requirements in the *analyze* phase.

Hence, a new design methodology must take into account the new service development methods to support transdisciplinary design activities across different life-cycle design phases. This relationship between new service development methods and life-cycle service design is denoted as R2 in Figure 3.

Design skills

Fourth, incorporating design skills in a design methodology for advanced service design is crucial, as emphasized by Baines et al. (2013) and Ingo Oswald Karpen et al. (2017), who demonstrated that the possession of design skills plays a critical role in determining key performance in this field. Supporting this argument, Spreitzer et al. (2012) suggest that it's important for internal stakeholders (e.g., designers, marketers, engineers) within a company to acquire the proper design skills that allow them to understand their work performance and development. As a result, training on these proper skills helps companies enhance their sustainable development. This also implies that the significance of all individuals involved, whether directly or indirectly, in the production of goods and/or services is recognized, promoting a business culture centred around advanced service design, rather than solely market orientation (Fernandes et al., 2019; Gilles & Christine, 2016).

However, the design skills that design teams need to perform design activities have rarely been studied, even though these design skills influence their performance in designing for advanced services (Karpen et al., 2017). According to Acklin (2010), the skills and mindset from different fields (e.g., service, engineering and industrial design) can function as an accelerator for the design of advanced services to the market by combining technological design and HCD. Besides, Coreynen et al. (2018) also stated that front-office staff need to master service skill sets beyond their professional skills to support in upscaling or in the successful adoption for the design of advanced services. Therefore, Chapter 4 made the contribution in the field of advanced service design by identifying the necessary design skills in a priority order for internal stakeholders, i.e., design teams, who need to comprehend and employ new service development methods proficiently (Table 2).

Therefore, a new design methodology is required to incorporate design skills—the ability of internal stakeholders who practice new service development methods to perform design activities across the life-cycle service design—to practically design for advanced services. This relation among design skills, stakeholder networks (internal stakeholders), new service development methods and life-cycle service design is denoted as R3 in Figure 3.

Above all, the weakness was often addressed in the literature, where the existing methodologies failed to fully grasp or only partially addressed the key design elements. To address this weakness, based on an ontology as a formal knowledge representation of all concepts and their relations (Gruber, 1993; Hartmann et al., 2017), a new multidimensional design methodology (DIMAND) is conceptually developed to formulate design knowledge that expresses the relations of the key design elements within the domain of advanced service design. For its implementation in practice, this design knowledge can be detailed through a grid matrix that has various applications, such as quality function deployment (Fan et al., 2019; Horvat et al., 2017), to show correlation relationships among multiple elements.

Thus, aiming to advance the body of research, Chapter 5 customized the correlation matrix so that these design elements would be interconnected to form DIMAND as a single and multidimensional structure, as presented in Figure 4. This structure can enable design practitioners and engineers to oversee the life-cycle service design, which possesses the two-dimensional (back and forth) interrelationship among design elements: stakeholder networks, new service development methods and design skills. This result addresses the second research question (RQ2): how are the key design elements and their relations incorporated in a single-view structure in accordance with a human-centric approach?

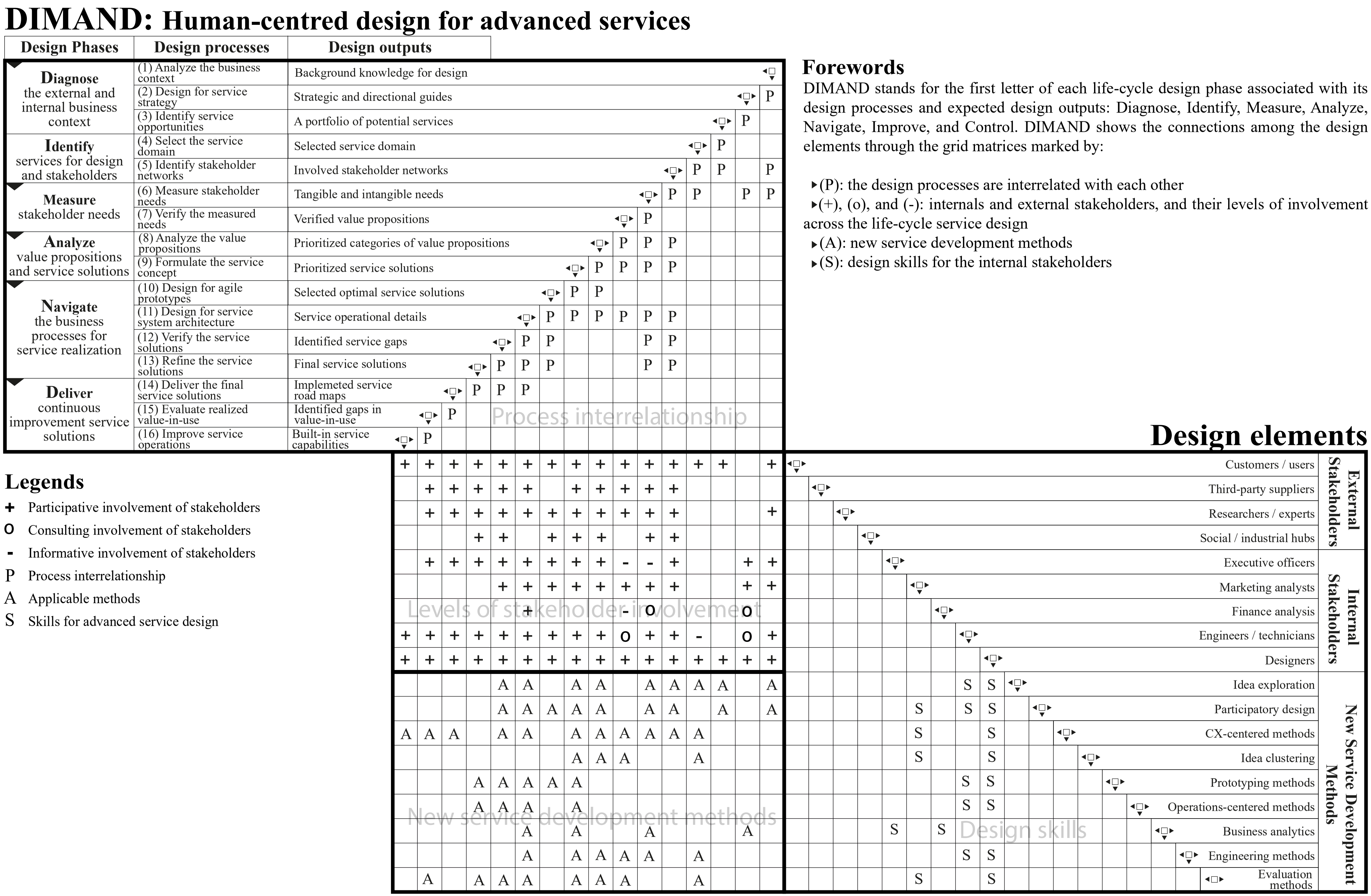
Chapter 5 presents DIMAND (Figure 4) through a hybrid research design that takes advantage of the body of knowledge in the literature through systematic reviews and meta-analyses of 21 existing design methodologies oriented to HCD for advanced services. These analyzed design methodologies are presented in the supplementary information (specifically, Appendix A, Chapter 5). The detailed research methodology of this present study is presented in Chapter 5.

Key findings

Life-cycle service design

As the first part of Figure 3, life-cycle service design must cover all life-cycle design phases and processes: planning and design, implementation and monitoring, product/service usage, feedback loops between phases. This requirement governs how the 21 existing design methodologies were analyzed to synthesize the life-cycle service design; the supplementary information (Appendix A, Chapter 5) contains a presentation of the design methodologies that have been reviewed. As a result, the left pillar of DIMAND (Figure 4) addresses HCD for advanced services, including the consecutive and interlinked design phases associated with design processes and outputs, forming the life-cycle service design.

This life-cycle service design includes from the diagnose and identify phase (planning), the measure and analyze phase (design), the navigate phase (implementation and monitoring), and the delivery phase (product/service usage). Moreover, the interrelationship of all design processes—here reflecting the feedback loops among them—is also displayed by the grid matrix, whose cells are marked by “P”; otherwise, there is no relationship addressed among them by the analyzed design methodologies. Process interdependencies (feedback loops) are exemplified in Figure 5, which shows the feedback loops among the design processes: “analyze the business context”, “design for service strategy”, and “identify stakeholder networks”.



DIMAND: Human-centred design for advanced services

Design Phases	Design processes	Design outputs																
Diagnose the external and internal business context	(1) Analyze the business context	Background knowledge for design																◂□▸
	(2) Design for service strategy	Strategic and directional guides															◂□▸	P
	(3) Identify service opportunities	A portfolio of potential services														◂□▸	P	
Identify services for design and stakeholders	(4) Select the service domain	Selected service domain													◂□▸	P		
	(5) Identify stakeholder networks	Involved stakeholder networks												◂□▸	P	P		P
Measure stakeholder needs	(6) Measure stakeholder needs	Tangible and intangible needs											◂□▸	P	P		P	P
	(7) Verify the measured needs	Verified value propositions										◂□▸	P					
Analyze value propositions and service solutions	(8) Analyze the value propositions	Prioritized categories of value propositions									◂□▸	P	P	P				
	(9) Formulate the service concept	Prioritized service solutions								◂□▸	P	P	P	P				
Navigate the business processes for service realization	(10) Design for agile prototypes	Selected optimal service solutions							◂□▸	P	P							
	(11) Design for service system architecture	Service operational details						◂□▸	P	P	P	P	P	P				
	(12) Verify the service solutions	Identified service gaps					◂□▸	P	P				P	P				
	(13) Refine the service solutions	Final service solutions				◂□▸	P	P	P				P	P				
Deliver continuous improvement service solutions	(14) Deliver the final service solutions	Implemeted service road maps			◂□▸	P	P	P										
	(15) Evaluate realized value-in-use	Identified gaps in value-in-use		◂□▸	P													
	(16) Improve service operations	Built-in service capabilities	◂□▸	P														

Process interrelationship

+	+	+	+	+	+	+	+	+	+	+	+	+	+		+	Customers / users
	+	+	+	+	+		+	+	+	+	+					Third-party suppliers
	+	+	+	+	+	+	+	+	+	+	+				+	Researchers / experts
			+	+		+	+	+		+	+					Social / industrial hubs
	+	+	+	+	+	+	+	+	-	-	+			+	+	Executive officers
				+	+	+	+	+	+	+	+			+	+	Marketing analysts
					+				-	o				o		Finance analysis
+	+	+	+	+	+	+	+	+	o	+	+	-		o	+	Engineers / technicians
+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	Designers
				A	A		A	A		A	A	A	A		A	Idea exploration
				A	A	A	A	A		A	A		A		A	Participatory design
A	A	A		A	A		A	A	A	A	A	A				CX-centered methods
							A	A	A			A				Idea clustering
			A	A	A	A	A									Prototyping methods
			A	A	A		A									Operations-centered methods
					A		A			A				A		Business analytics
					A		A	A	A	A		A				Engineering methods
	A		A	A	A		A	A	A			A				Evaluation methods

Levels of stakeholder involvement

New service development methods

Design elements

◂□▸																									Customers / users	External Stakeholders
	◂□▸																								Third-party suppliers	
		◂□▸																							Researchers / experts	
			◂□▸																						Social / industrial hubs	
				◂□▸																					Executive officers	Internal Stakeholders
					◂□▸																				Marketing analysts	
						◂□▸																			Finance analysis	
							◂□▸																		Engineers / technicians	
								◂□▸																	Designers	
							S	S	◂□▸																Idea exploration	New Service Development Methods
					S		S	S		◂□▸															Participatory design	
					S			S			◂□▸														CX-centered methods	
					S			S				◂□▸													Idea clustering	
							S	S					◂□▸												Prototyping methods	
							S	S						◂□▸											Operations-centered methods	
				S		S									◂□▸										Business analytics	
							S	S								◂□▸									Engineering methods	
					S			S									◂□▸								Evaluation methods	

Design skills

Forewords

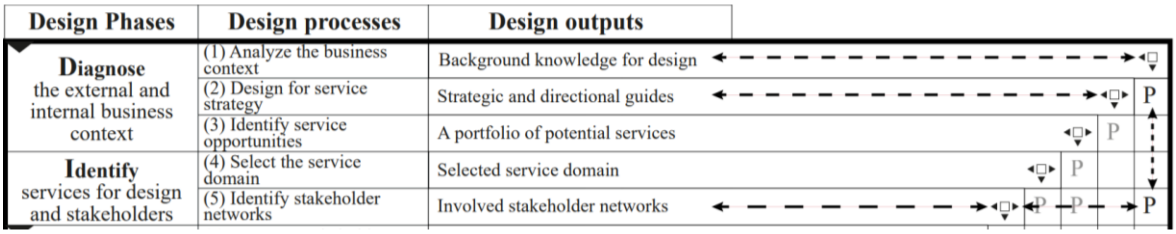
DIMAND stands for the first letter of each life-cycle design phase associated with its design processes and expected design outputs: Diagnose, Identify, Measure, Analyze, Navigate, Improve, and Control. DIMAND shows the connections among the design elements through the grid matrices marked by:

- ▸(P): the design processes are interrelated with each other
- ▸(+), (o), and (-): internals and external stakeholders, and their levels of involvement across the life-cycle service design
- ▸(A): new service development methods
- ▸(S): design skills for the internal stakeholders

Legends

- **+** Participative involvement of stakeholders
- **o** Consulting involvement of stakeholders
- **-** Informative involvement of stakeholders
- P Process interrelationship
- A Applicable methods
- S Skills for advanced service design

FIGURE 4
A multidimensional design methodology for advanced services (DIMAND). For instructions on how DIMAND works in practice, see the supplementary information in Chapter 5



Design Phases	Design processes	Design outputs
Diagnose the external and internal business context	(1) Analyze the business context	Background knowledge for design
	(2) Design for service strategy	Strategic and directional guides
	(3) Identify service opportunities	A portfolio of potential services
Identify services for design and stakeholders	(4) Select the service domain	Selected service domain
	(5) Identify stakeholder networks	Involved stakeholder networks

FIGURE 5

An illustration of process interdependency. A cutting plane of DIMAND (Figure 4) that exemplifies how the design processes are a two-dimensional interrelationship through the grid matrices, which can be seen by reading the path of the two-directional dotted arrows as an example. This reading pattern is applicable to the rest of the connections among the design elements in DIMAND

Specifically, Acklin (2010) and Iriarte et al. (2018) paid attention to the diagnose and identify phase. First, Acklin (2010) proposed a design methodology whose first design process was to analyze the business context for the acquisition of background knowledge for design: to understand what a company has learned so far and its business ecosystem (e.g., markets, customer trends). This understanding can enable the company to design for service strategy (e.g., communication and brand strategies). Second, Iriarte et al. (2018) highlighted their design methodology whose starting design process was to analyze the business context by taking a snapshot of a detailed investigation of the business: competitive advantages and potential value propositions for advanced services in the machinery industry. According to the authors, this investigation can help the company properly identify stakeholder networks: key customer staff responsible for the purchase of the solution on offer (e.g., top managers, technicians, and operations personnel), and internal stakeholders (e.g., quality manager, operations manager, product manager, technicians). Instead of focusing on the *diagnose* and *identify* phase, Yu (2018) focused only on the *measure* and *analyze* phase (design). The author proposed a HCD methodology whose starting design task was to measure stakeholder needs in both functional and non-functional requirements of students in terms of a library service (e.g., experiences, opinions, user perception). Subsequently, the measured requirements were the design inputs used to analyze the value propositions according to user contexts, such as physical conditions, technical capabilities, and cognitive links among product attributes, consequences, and goals.

Hence, such interdependencies among design processes can help designers coordinate and integrate the outcomes of various design processes, since the results of one process may impact those of another. Most importantly, DIMAND focuses on life-cycle service design and the interrelationships among design processes (referred to as "P"), which enables designers to consider the entire life-cycle perspective and incorporate process dependency and contingency planning into their design activities. The detailed description of how DIMAND works in practice is presented in the supplementary information (Appendix B, Chapter 5).

Stakeholder networks

For the second key design element of Figure 3, stakeholder networks must consider both internal and external stakeholder networks, and their involvement levels—an informative level, a consultative level, a participative level—across the life-cycle service design. This consideration governs how the included design methodologies were analyzed to synthesize the stakeholder networks. Similar to the synthesis of the life-cycle service design, the design element of the stakeholder networks has been built by extracting and synthesizing the

"Stakeholders" across the design processes, here as addressed by the analyzed design methodologies oriented to HCD (Appendix A, Chapter 5).

Thus, DIMAND (Figure 4) embeds the stakeholder networks that are connected with the life-cycle service design (the left pillar) through the same grid matrices of DIMAND, hence realizing the relation between them (R1 in Figure 3). By doing this, two design decisions related to the involvement of stakeholders can be made: (i) who will be involved in which specific design process and/or which design process asks for the participation of whom and (ii) what the level of involvement for each stakeholder in the according design process. The answer to these two questions is given by the grid matrices, whose cells are marked by the symbols of "+" (participative), "o" (consulting) and "-" (informative); otherwise, there is no relationship addressed among them by the reviewed design methodologies.

In the analyzed analyzed design methodologies, the role of finance analysts was not addressed across the life-cycle service design, except for the work of Chew (2016) who highlighted the importance of finance analysts whose consulting roles (o) were to cooperate with other design teams (e.g., market analysts and IT technicians). This cooperation was intended to design for service strategy (e.g., business and market models)—and measure stakeholder needs, verify the measured needs, analyze the value propositions and formulate the service concept. Moreover, Chew (2016) also appreciated the participative role (+) of finance analysts required to design for service system architecture in terms of the monetization process linked to the business strategy. Although Iriarte et al. (2018) did not discuss the role of finance analysts in the design team, they explicitly highlighted the participative involvement (+) of executive officers across departments (e.g., business managers, project managers, sales managers) to analyze the business context in the very first design phase. They also underlined the participative roles (+) of researchers who offered their design knowledge to facilitate their case company to analyze the business context and other design processes. Instead of highlighting an individual role, cooperation among design teams has also been noted as essential, as emphasized by Papazoglou et al. (2020). Specifically, marketing analysts, designers and engineers—who are responsible for manufacturing and maintenance—work participatively together with external stakeholders (e.g., customers, third-party suppliers) to verify whether or not customer needs can be fulfilled with the company capability (e.g., product-service design, production scheduling and capability, commissioning).

To this end, DIMAND has been designed to provide comprehensive guidance on stakeholder involvement throughout the life-cycle service design, including clear instructions on assigning involvement roles for each stakeholder. In addition to external stakeholders like customers and third parties, DIMAND emphasizes the importance of involving and understanding internal actors such as executive officers, marketers, engineers in manufacturing and maintenance, and product engineering. This approach fosters value co-creation capabilities in advanced service design, as called for by Fernandes et al. (2019) and Gilles & Christine (2016).

New service development methods

For the third key design elements (Figure 3), the new service development methods must be both non-engineering (e.g., participatory design, interviews) and engineering methods (e.g., quality function deployment, statistics). This requirement shapes the way new service development methods were synthesized. In particular, this synthesis was realized by categorizing the "design methods" of the analyzed design methodology extracted from the supplementary information (Appendix A, Chapter 5).

As a result, the bottom of the right pillar (design elements) of DIMAND (Figure 4) integrates the new service development methods. This integration interlinks with the life-cycle service design through the grid matrices, whose cells are marked by "A" in DIMAND; otherwise, there is no relationship addressed among them as seen by the analyzed papers. Thus, the integration realizes the relation between them (R2 in Figure 3).

Specifically, Hartono (2020) replied on the method group "idea exploration" (e.g., face-to-face surveys, interviews) to measure stakeholder needs (e.g., the quality perception of clients about airport services); this relationship is symbolized by "A" in DIMAND. Similarly, Camussi et al. (2020) also applied the same method of "idea exploration" (e.g., ethnographic observations, narrative interviews) to measure stakeholder needs by capturing the stories, needs and desires of customers in the healthcare system. Alternatively, Kumar and Maskara (2015) applied the both method groups: idea exploration (e.g., ethnography, observation and interview) and participatory design (e.g., workshop techniques). These human-centric design methods allowed the authors to measure stakeholder needs regarding functional and non-functional requirements in design for healthcare software, such as technology adoption, painful areas in usability and human factors (e.g., values, beliefs, attitudes, user experience and clinician preferences).

By realizing the interconnection between the new service development methods and the life-cycle service design, one can seek what the design method can be used for, hence enabling the execution of the specific design processes. In the reverse direction, one can also answer the following inquiry: What design methods can a design process apply? For example, the design methods for "idea clustering" (e.g., affinity diagram, Kano model) may be used by four design processes—*select the service domain*, *verify the measured needs*, *analyze the value propositions*, and *formulate the service concept*—in the life-cycle service design, which is symbolized by "A" in DIMAND. In the reverse direction, to analyze the business context, one may want to apply one or more design methods of "idea exploration" (e.g., field research, desk research) and "participatory design" (e.g., workshops, Barcamps) to acquire the design output: background knowledge for design. A design practitioner can also apply "engineering methods", such as hierarchical task analysis, to measure stakeholder needs in terms of user physical tasks and goals. For some advanced services related to social-technical systems (e.g., digital dashboard for decision making), other engineering methods, such as the functional resonance analysis method (Piera et al., 2022), may be required to measure the time-stamp information between cognitive workload and technical resources embedded in such advanced services.

As a result, DIMAND is not only the life-cycle service design, but it also shows how the design phases and processes can be supported and implemented by a set of new service development methods that are practical and have been demonstrated to work in the literature. This enables designers and engineers to learn about a wide range of service and engineering-specific methods that support the transdisciplinary approach required for advanced service design.

Design skill

For the last class of key design elements (Figure 3), design skills represent the ability of internal stakeholders (design teams), who practice new service development methods to perform design activities across the life-cycle service design. Therefore, as mentioned in Section 2.2, specifically, based on Table 2, there are nine groups of new service development methods used to form corresponding skills among five groups of design teams in a priority order.

Based on Table 2, DIMAND (Figure 4) is equipped with design skills by connecting the internal stakeholders (design teams) with the new service development methods. This connection realizes the relation between them (R3 in Figure 3). As can be seen by the “S” symbols integrated into DIMAND, this reveals the transdisciplinary design team, in which two or three job roles (design teams) should practice a specific group of service development methods; this also shows how a company should make decisions about the training priority among its design teams.

Creating a transdisciplinary design team can leverage the skills and perspectives from various fields such as service, engineering, and industrial design to accelerate the development of advanced services for the market. This is achieved by combining technological design with human-centred design principles (Acklin, 2010). Among the design teams, except for the skill set of “business analytics” (e.g., game theory, contingency theory), designers are required to practice all skill sets. In line with this result, Calabretta, G. and De Lille (2016) suggested a much broader role for design professionals in the company to enable the transition process towards the effective design of advanced services.

In addition to designers, the roles of engineers and/or technicians and marketing analysts were also emphasized. The engineers who may come from different departments (e.g., research and development, manufacturing and maintenance, and quality assurance) should not only be qualified in technical skills, including prototyping methods, operations-centred methods, and engineering methods. But they should also understand what customers want in both the functional (e.g., technical problems, service quality reports) and non-functional requirements (e.g., user perception, cognitive domain). Comprehending customer requirements can be more effective by training the skill sets of “idea exploration” (e.g., focus-group and interview techniques) and “participatory design” (e.g., service design labs and workshops) for both engineers and marketing analysts. Coreynen et al. (2018) also stated that front-office staff need to master service skill sets beyond their professional skills to support in upscaling or in the successful adoption for the design of advanced services.

To this end, DIMAND is a novel HCD methodology that assists design practitioners in building the company's internal service capability by determining who needs to know what design methods and prioritizing training for cross-functional design teams based on the identified skill sets represented by the "S" symbols in DIMAND (Figure 4). This capability building process is aimed at developing and nurturing a transdisciplinary design team, where diverse skills and mindsets from various fields can work together to accelerate the design of advanced services.

Conclusion

To sum up, DIMAND addresses (1) life-cycle service design that is interrelated with other key design elements—(2) stakeholder networks; (3) new service development methods; and (4) design skills—in a single-view structure with a human-centric approach. Specifically, the characteristics of DIMAND are addressed as follows:

First, DIMAND addresses life-cycle service design and the interconnection among the design processes, facilitating practitioners in keeping the life-cycle perspective in mind and taking process dependency and contingency planning into account in their design decisions.

Second, DIMAND is equipped with complete information about stakeholder involvement, offering a comprehensive guideline on how to oversee and plan "who will do what" across the life-cycle service design. Beyond the external stakeholders (e.g., customers, third parties), DIMAND encourages design practitioners to take into account the involvement and understanding of internal actors (e.g., executive officers, marketers, engineers and technicians, designers) in their design decisions, fostering the business culture perspective on advanced service design in addition to the market orientation.

Third, DIMAND is not only about life-cycle service design but also shows how the design processes can be supported and implemented by sets of new service development methods that are viable and proven in literature. This allows design practitioners and engineers to be aware of a wide range of service- and engineering-specific methods (e.g., service blueprints, TRIZ, Lean, manufacturing blueprints) that support a transdisciplinary approach required for advanced service design.

Fourth, DIMAND also facilitates design practitioners in building internal service capability (who needs to know and/or practice what) through these skill sets and making decisions on training priority under their business resource constraints. This capability building helps companies develop and nurture the transdisciplinary design team in which the skills and mindset from different fields function as an accelerator for the design of advanced services.

To this end, DIMAND integrates all interdependent key design elements into a unified structure, as demonstrated in Figure 4, that aligns with the human-centric approach. This enables design practitioners and engineers to maintain coherence in life-cycle service design and the relationships among key design elements when making design decisions, resulting in more effective advanced service design.

Next research

At this stage, the present thesis addresses the second research question (RQ2): how are the key design elements and their relations incorporated in a single-view structure in accordance with a human-centric approach? Lastly, Chapter 6 provides a summary and validation of both the thesis objectives and the usefulness of DIMAND. The subsequent three chapters present the complete content and research contributions in order of corresponding publications: Nguyen, Lasa, & Iriarte (2022); Nguyen, Lasa, Iriarte, Atxa, et al. (2022a); Nguyen, Lasa, Iriarte, Atxa, et al. (2022b).

CHAPTER 3

Human-centred design in industry 4.0: case study review and opportunities for future research

Brief summary

Active work on developing methods, exploring influencing factors, and proving the effectiveness and efficiency regarding HCD show the increasing awareness of human roles in Industry 4.0 (Chart 1). Although numerous review papers portrayed the key developments over recent years, they focused on the reflection of emerging trends based on bibliometric results, debates, and priorities in their own research scope with their defined disciplines (Victorelli, Dos Reis, Hornung, et al., 2020; Zarte et al., 2020). However, the review work does not pay attention to publications whose case studies contain a tremendous source of useful information.

Therefore, the present study is one of the unique attempts to bridge the gap through the literature characteristics and the lessons learnt derived from an expository of case studies of HCD in the context of Industry 4.0. In order to sufficiently cover the research topic and provide evidence with a minimal amount of subjectivity and bias, this research performs systematic literature review (SLR) in which a special unit of analysis is given to the case studies. Based on SLR, a total of 265 papers were identified. After careful evaluation, 188 papers were considered irrelevant and excluded from the analysis, while 77 were deemed relevant and included in the review within the context of Industry 4.0. Out of the 77 included papers, 43 were found to contain case studies that specifically focused on HCD. The in-depth review on these case studies delivered the contributions in three ways.

First, the approach to HCD is characterized as transdisciplinary and multidimensional. This finding is evidenced by the growing research interest across different disciplines and industries, examining various levels of analysis related to HCD, including product, workstation, company, and society. The transdisciplinary approach addresses the interest in extending the research boundaries of various dimensions of HCD in literature: human diversity, physical to cognitive ergonomics, economics, manufacturability, and social and human-related sustainability. Additionally, the multidimensional approach of HCD is also observed by the cross-layer level of research—the product and/or service, workstation, company to social level—in which humans are centred.

Second, the transdisciplinary and multidimensional approach is also reflected by the in-depth review of case studies: the emerging trend, the design methods and lessons learnt. The review of the 43 case studies unfolds the emerging research themes—HCD, PSS, user-centred design, human-robot collaboration, human-in-on-the-loop, and human-machine interface—that deal with the challenges of personalization, servitization, sustainability, and smart manufacturing in the context of Industry 4.0. Table 1 shows the most emerging research trend that is HCD for PSS, leading to the scope of present thesis on HCD for PSS whose special case is advanced services.

Besides, the in-depth review also captures the wide range of design methods that are categorized in the four generic groups—discovery, clean-up, engineering, experiment—to tackle different problems scattered across different life-cycle design phases. The variety in both quantitative and qualitative design methods (engineering and non-engineering design methods) allows design practitioners to have effective design towards human diversity, ergonomics, economics, manufacturability, and sustainability.

Therefore, the present study calls for better adaptation to the design challenges by having cross-disciplinary collaborative research and/or improving the transdisciplinary skill sets of engineers and design practitioners. This finding motivates the next research work of identifying design skills presented in Chapter 4.

The lessons learnt from the in-depth review of case studies encapsulate various research results associated with limitations that are captured and harmonized in homogeneous groups: six groups of research results and four groups of research limitations. The research results are categorized into six groups: exploration of design success factors, achievement of engineering objectives, provision of supporting design frameworks, validation of the effect of human diversity on design, provision of transdisciplinary frameworks, and visualization of design scenarios. The exploration of design success factors is the most significant finding (22 out of 43 reviewed case studies) that was related to the identification of key design elements regarded as design success factors: life-cycle service design, stakeholder networks, and new service development methods (design practice).

Figure 2 shows these key design elements that shed light on how successful HCD can be applied in different settings, particularly in the context of PSS whose special case is advanced services. This finding directly addresses RQ1: What are the key design elements of an effective HCD methodology for advanced services? As mentioned from the previous paragraph, the research motivation to identify design skills, also posed by Baines et al. (2013) and Ingo Oswald Karpen et al. (2017), leads to the next research work presented in Chapter 4. This work addresses RQ1**.**

When it comes to the four groups of research limitations, the reviewed case studies also acknowledged their research limitations—limited statistical power in result validation, lack of generalizability of research findings, further requirements of the supporting methods, lack of validation of the effectiveness—to enhance the robustness of the research findings. The practical application of these studies is not consistently implemented and the network of studies lacks a cohesive structure for comprehensive accumulation.

Third, the present study highlights the need for future research regarding HCD to build on the lessons learned from previous work, in order to advance research contributions in the coming years. Specifically, the study calls for a new research approach to HCD, which must fulfill its transdisciplinary and multidimensional characteristics through a systematic identification of key design elements: life-cycle service design, stakeholder networks, and new service development methods (design practice). This call leads to RQ2: How are the identified key design elements and their relations incorporated in a single-view structure in accordance with a human-centric approach? The answer to this research question is presented in Chapter 5.

Despite the rigor, relevance, and scope of this study, there are some acknowledged limitations. First, the strict protocol of systematic literature review (SLR) may have resulted in overlooking some relevant papers. Second, the study limited the review process to peer-reviewed journal articles to ensure the quality of the publications. Third, the present study acknowledges that the selection of the topic, definition of search terms, and interpretation of the results are inseparable from our previous knowledge on the topic.

The full contents of this study are presented below.

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Human-centred design in industry 4.0: case study review and opportunities for future research

Hien Nguyen Ngoc[1] · Ganix Lasa[1] · Ion Iriarte[1]

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Abstract

The transition to industry 4.0 has impacted factories, but it also affects the entire value chain. In this sense, human-centred factors play a core role in transitioning to sustainable manufacturing processes and consumption. The awareness of human roles in Industry 4.0 is increasing, as evidenced by active work in developing methods, exploring influencing factors, and proving the effectiveness of design oriented to humans. However, numerous studies have been brought into existence but then disconnected from other studies. As a consequence, these studies in industry and research alike are not regularly adopted, and the network of studies is seemingly broad and expands without forming a coherent structure. This study is a unique attempt to bridge the gap through the literature characteristics and lessons learnt derived from a collection of case studies regarding human-centred design (HCD) in the context of Industry 4.0. This objective is achieved by a well-rounded systematic literature review whose special unit of analysis is given to the case studies, delivering contributions in three ways: (1) providing an insight into how the literature has evolved through the cross-disciplinary lens; (2) identifying what research themes associated with design methods are emerging in the field; (3) and setting the research agenda in the context of HCD in Industry 4.0, taking into account the lessons learnt, as uncovered by the in-depth review of case studies.

Keywords Human-centred design · Industry 4.0 · Case study review · Research opportunities

Introduction

A challenge of manufacturing today is adapting to an increasingly fluctuating environment and diverse changes to meet the demands of the market. Product life cycles are getting shorter while production batch sizes are getting smaller with dynamic product variants associated with increasing complexity, which is challenging the traditional production systems (Benabdellah et al., 2019; Kuhnle et al., 2021; Ma et al., 2017; Prinz et al., 2019; Windt et al., 2008; Zhu et al., 2015). To manage these dynamics, the industrial concept of Industry 4.0 has come about and has been accepted in both research and industry, a trend linked to digitalization and smart systems that could enable factories to achieve higher production variety with reduced downtimes while improving yield, quality, safety, and decreasing cost and energy consumption (García-Magro & Soriano-Pinar, 2019; Järvenpää et al., 2019; Napoleone et al., 2020; Oztemel & Gursev, 2020; Park & Tran, 2014). Although the adoption of Industry 4.0 in manufacturing reveals positive outcomes, the increased complexity as a collateral effect has also brought many challenges (Bednar & Welch, 2020; Cohen et al., 2019; Fernandez-Carames & Fraga-Lamas, 2018; Mourtzis et al., 2018; Wittenberg, 2015). One of the challenges is to put humans properly at the centre of smart manufacturing design (Grandi et al., 2020; Pacaux-Lemoine et al., 2017; Paelke et al., 2015; Peruzzini et al., 2019; Varshney & Alemzadeh, 2017). An approach to address this challenge is known as HCD. According to International Organization for Standardization (2019), HCD is a multidisciplinary approach incorporating human factors and ergonomics knowledge and techniques to make systems usable. However, the design complexity in smart systems can occur in both directions, where in one direction the human must be able to effectively

✉ Hien Nguyen Ngoc
nhneguyen@mondragon.edu

Ganix Lasa
glasa@mondragon.edu

Ion Iriarte
iiriarte@mondragon.edu

[1] Design Innovation Center (DBZ), Mondragon Unibertsitatea - Faculty of Engineering, Loramendi, 4, 20500 Arrasate-Mondragón, Gipuzkoa, Spain

cooperate with other existing physical system components and simultaneously exchange data with system informatics for hybrid decision making (Fernandez-Carames & Fraga-Lamas, 2018; Schulze et al., 2005; Zheng et al., 2018). The reverse direction is that the design of such smart systems must be capable of sensing and responding to the trust levels of humans they interact with in order to result in more productive relationships between the human and other smart components (Chang et al., 2017; Rogers et al., 2019; Seitz et al., 2021; Song et al., 2016; Van Acker et al., 2020).

Numerous contributions have been written on Industry 4.0 areas; however, the majority of them focus on the technical aspects in which human factors are commonly underestimated (Bhamare et al., 2020; Grandi et al., 2020; Pacaux-Lemoine et al., 2017; Peruzzini et al., 2019; Theuer et al., 2013). There is an increasing concern about how human factors are barely considered in design for products and/or services and poorly addressed in manufacturing, causing complex problems with often unknown consequences across different industrial contexts: nuclear accidents (Wu et al., 2016), market failures in new product development (García-Magro & Soriano-Pinar, 2019), robotic-surgery-related adversities (Varshney & Alemzadeh, 2017), technological accidents during machine manipulation (Pacaux-Lemoine et al., 2017), and interaction issues among humans and smart systems (Jung et al., 2017; Rogers et al., 2019; Streitz, 2019).

The phenomenon of Industry 4.0 reflects contemporary design contexts that frequently contain complex interdependencies of human and non-human actors—internet of thing (IoT) devices, digital and physical environments—shaping the framework of human roles and socio-technical systems (Cimini et al., 2020; Coulton & Lindley, 2019; Jwo et al., 2021; Kong et al., 2019; Kymäläinen et al., 2017). However, this does not mean that the existing concepts of design—for example, design for manufacturing and assembly (Favi et al., 2021), or a traditional design process that considers existing solutions to fulfil the needs of the largest group (Lorentzen & Hedvall, 2018)—are redundant. They have evolved and enlarged the scope of design: manufacturability fosters the collaboration of design and manufacturing operations, taking the perspectives of efficiency, effectiveness and economics into account (Chen et al., 1995; Venkatachalam et al., 1993); social sustainability addresses design for quality of human life by considering transdisciplinary relationships with human diversity (Demirel & Duffy, 2013; Martin et al., 2013; Papetti et al., 2020). These new requirements have impacted the factories themselves, but they affect the entire value chain, from the product design and development process through market segmentation to manufacturing and product disposal management (Bauer et al., 2019; Kong et al., 2019; Pereira Pessôa & Jauregui Becker, 2020). In this sense, for transitioning to sustainable manufacturing processes and consumption, human-centred factors play a core role in the achievement of sustainability-oriented operations throughout the supply chain (Bednar & Welch, 2020; Ceccacci et al., 2019; Grandi et al., 2020; Gualtieri et al., 2020; Lin, 2018; Rossi & Di Nicolantonio, 2020).

To address human-related roles in the context of Industry 4.0, there is a constantly growing interest in research and industrial practices where humans are placed at the centre of design across disciplines. This is manifest in the substantial body of literature providing signposts of theoretical frameworks and models, implementation methodologies, and case studies in cross-disciplinary contexts. The scope of the research is extensive: customer-centric business models associated with customer involvement in design (Adrodegari & Saccani, 2020; Grieger & Ludwig, 2019; Saha et al., 2020; Santos et al., 2018); smart design engineering in which the users and emotional interactions are empowered (Benabdellah et al., 2019; Pereira Pessôa & Jauregui Becker, 2020); technology design in which users are centred (Chen & Duh, 2019; Rogers et al., 2019); interaction designs among operators and smart manufacturing components (Klumpp et al., 2019; Rossi & Di Nicolantonio, 2020); human-centred designs for product development (Chen et al., 2016; Wu et al., 2013); data processing by which humans remain the first design consideration of a data-driven approach (Crabtree & Mortier, 2015; Victorelli et al., 2020b); sustainability in social-technical manufacturing contexts, including social robotic interactions with humans (Bednar & Welch, 2020; Leng & Jiang, 2017; Richert et al., 2018; Streitz, 2019).

Even though a wide array of studies has been created and published, these studies have become disconnected from other studies after publication. As a consequence, these studies in industry and research alike are not regularly adopted, while the network of studies is scattered and diffused without forming any comprehensive structure. Although numerous review papers portrayed the key developments regarding HCD over recent years, they focused on the reflection of emerging trends based on bibliometric results, debates, and priorities in their own research scope with their defined disciplines. Recently, Zarte et al. (2020) conducted SLR to structure design principles for HCD while Victorelli et al. (2020a) provided an understanding of human-data integration with bibliometric analysis. Other representative review studies include Benabdellah et al. (2019), Duque et al. (2019), Kadir et al. (2019), Bazzano et al. (2017). However, the current work does not pay attention to publications whose case studies contain a tremendous source of useful information. The results of a case study can have a very high impact on exploring in-depth conceptual testing and refinement associated with lessons learnt (Kadir et al., 2019; Tetnowski, 2015; Williams, 2011; Yin, 2018), something that deserves to be treated as a special unit of analysis in the review process. Moreover, the review papers also pointed out their own methodological limitations, leading to the call for future research priorities in identifying and deepening the research outcomes of HCD through the cross-disciplinary lens.

To take the perspective of HCD under the transition to Industry 4.0 and simultaneously respond to said call, we contribute to the research through a rigorous review of case studies—to capture the lessons learnt—that have been conducted so far in the literature. The objective is to pave the way for the ongoing developments around the concept and also explain its journey in a systematic and well-rounded methodology. To achieve this objective, we review the existing scientific body of knowledge by:

- providing insight into how the literature has evolved through the cross-disciplinary lens
- identifying what research themes associated with design methods are emerging in the field
- setting the research agenda in the context of HCD in Industry 4.0, taking into account the lessons learnt, as uncovered by the in-depth review of case studies

To achieve the above and contribute to the body of knowledge regarding the HCD domain, this article begins with HCD's fundamental concepts, which indicate for researchers diverse perspectives on HCD across the value chain in the context of Industry 4.0. The next section presents a strict protocol of SLR that ensures a sufficient amount of quality publications for the analysis. "Literature characterization of human-centred design in industry 4.0" section digs into the literature to unfold the characteristics of HCD. Subsequently, the in-depth review expresses important facts of HCD in the context of Industry 4.0: emerging research schemes among concepts of HCD, diverse design methods and lessons learnt. This article concludes with a comparative discussion of the papers and suggests opportunities for further research.

Human-centred design in industry 4.0

Nowadays, the fourth industrial revolution develops highly connected resources, integrates smart components and enables interoperability in cyber-physical systems (CPSs) in the twenty-first century (Campbell 2021; Cruz Salazar et al., 2019; Derigent et al., 2020; Duque et al., 2019; Pereira Pessôa & Jauregui Becker, 2020). The changes that trigger Industry 4.0 have impacted different domains throughout the value chain. First, an autonomous system—embedding smart components in CPSs equipped with autonomous capability—achieves a specified goal independently without any human intervention (Gamer et al., 2020; Park & Tran, 2014). However, human intelligence and intervention remain a key role because of the safety, security, social aspects and uncertainties posed by such autonomous systems (Fosch-Villaronga et al., 2020; Gil et al., 2019; Nahavandi, 2017; Santoni de Sio & van den Hoven 2018; Weichhart et al., 2019). Along with advanced technologies in such smart systems, the role of humans has changed and shifted from low-level operations—which can be dangerous, dirty, difficult, and dull tasks—to high expertise and safe tasks (Bauer et al., 2019; Campbell 2021; Nahavandi, 2017; Zhang et al., 2017). This phenomenon highlights two different concepts of HCD: *human-in-the-loop* and *human-on-the-loop systems* (HioTL). The human-in-the-loop system is a system in which a machine executes a task for a specific command and then stops for the human order before continuation. On the other hand, the human-on-the-loop system is an autonomous system that executes a task independently and completely, while the role of humans can provide expertise not available to the system and can respond to issues that the system is unaware of (Kong et al., 2019; Nahavandi, 2017; Richter et al., 2018; Streitz, 2019; Vanderhaegen, 2019). An autonomous system should not imply the exclusion of the human, but it should allow for a seamless integration of humans in both operational levels of the process monitoring and strategic levels of orchestration in the aggregate plan. This approach enables high levels of human collaboration to achieve the common key performance indicators of manufacturing while meeting internal constraints (Gervasi et al., 2020; Pacaux-Lemoine et al., 2017).

In addition, the smart robots work safely with humans in collaborative production systems to autonomously and seamlessly perform collaborative tasks working towards common goals (Boschetti et al., 2021; Cohen et al., 2019; Gervasi et al., 2020; Wojtynek et al., 2019). These collaborative robots, often called *cobots*, relieve the factory workers from the low-level tasks to work side-by-side with humans in order to increase the workstation performance: production pace, efficiency, and higher throughput. In this context, design for the collaboration is well known as *human–robot collaboration* (HRC), which is also interchangeably called *human–robot interaction* (Cohen et al., 2019; Gervasi et al., 2020). Beyond the physical interactions, the collaboration design also enables the robots and humans to share knowledge and learn from others, and so work towards social sustainability, i.e., discussions and accommodation with others' perspectives (Fosch-Villaronga et al., 2020; Gualtieri et al., 2020; Richert et al., 2018; Weichhart et al., 2019).

In addition to smart systems and cobots, the industry and research alike pose new requirements and means of interactive interfaces among human and non-human actors (e.g., machines, smart devices) to deal with the new challenges: interdependent interactions with complex information, and natural and intuitive communication (Diegel et al., 2004; Haslgrubler et al., 2018; Ong et al., 2020; Weichhart et al., 2019). In the earlier development, the information systems interfaces are usually designed by the technology-oriented approach that adapts humans to the equipment. This lack of consideration of the human results in lower-than-expected manufacturing system performance and an increasing possibility of error rates (Chen & Duh, 2019; Oborski, 2004; Wu et al., 2016). Therefore, putting humans at the centre of interface design is the concept of the *human–machine interface* (HMI), which allows humans to understand and operate a machine in a digital manufacturing context. Design for HMI requires a transdisciplinary approach that takes various disciplines into account: cognitive psychology, industrial design, information processing graphics, human factors, and ergonomics (Oborski, 2004; Ong et al., 2020; Wu et al., 2016).

Beyond industrial applications, the user-friendly design of HMI is important in various domains—desktop, web engineering, and services—with which its application boundary is very blurred (Chang & Lee, 2013; Chang et al., 2017; Hoffmann et al., 2019). Basically, one of the key measurements to understand the degree to which the design of HMI meets usage requirements is its usability, which focuses on functional indicators: usefulness, efficiency, effectiveness, and the learning curve of the user interface. The deeper concept of user multidimensional experience—which considers users' emotional and psychological responses—is getting increasing attention and is also known as the core concept of *user-centred design* (UCD) (Chen, 2016; Kymäläinen et al., 2017; Lin, 2018; Paelke et al., 2015; Zheng et al., 2018). UCD, also interchangeably called *user-centrality*, embraces the user's needs and involvement as the centre of the co-designing development process (Mazali, 2018; Wu et al., 2016) in order to enhance user acceptability and acceptance. While the former is a prior mental representation that users have before interacting with a product and/or service, the latter is an evaluation after a real interaction with the design has taken place (Van Acker et al., 2020).

From the perspective of life-cycle design, the increasing variability of products and varying expectations of customers have impacted development and manufacturing at different stages, requiring new solutions that enhance the value of the customer's interaction with the product along its life cycle (Benabdellah et al., 2019; Chaudhuri et al., 2019; Fernandez-Carames & Fraga-Lamas, 2018; Pezzotta et al., 2018; Zhu et al., 2015). In this evolving scenario, manufacturers navigate from product-oriented development to the servitization phenomenon in which the concept of *product-service systems* (PSS) is a result of product and service integration. PSS is capable of fulfilling the customer's present requirements while being adaptable to future needs and necessities through all their life-cycle stages (Cheah et al., 2019; Haber & Fargnoli, 2019; Leoni, 2019; Mourtzis et al., 2018; Pezzotta et al., 2018; Zhu et al., 2015). PSS requires a human-centred design thinking process that not only generates the value-in-use to the customer through the identification of the latent requirements, but also manages the stakeholders and the technical feasibility (Cheah et al., 2019; Santos et al., 2018). The approach of HCD, such as service design, plays an important role in the design of service-oriented value propositions by providing a set of methods to improve customer experience and understand emerging social trends (Iriarte et al., 2018).

The value chain itself is being reconfigured because the type of value exchange is shifted from selling products to providing services in order to optimize competitiveness through market segmentation strategies towards customer personalization. Smart PSS allows for a completely new relationship between manufacturers and customers and thus enables new business models towards *customer-centricity* that facilitate customer-focused and co-creation relationships towards sustainability for business, customers, and stakeholders (Anke, 2019; Bednar & Welch, 2020; Benabdellah et al., 2019; Grieger & Ludwig, 2019; Ma et al., 2017; Saha et al., 2020). This phenomenon is enabled by the ubiquity of digital technologies that allows for a fundamental shift in the business landscape in which the individual customer is at the centre of design activities, at the point of origin, and an active participant across different business processes: innovation, development, management, and production to deliver "smartness" values (Brenner et al., 2014; Mazali, 2018; Zheng et al., 2018).

Smartness is a socio-technical phenomenon—in which the production processes and the products themselves are technical aspects—that impacts society's awareness of sustainability in terms of the environmental, social, and economic aspects (Bednar & Welch, 2020; Fu et al., 2019; Gualtieri et al., 2020; Pereira Pessôa & Jauregui Becker, 2020). There will be a need for a strategic balance between shorter- and longer-term desires, values, and policies, and the interests of different groups of stakeholders. Technology alone cannot give an organization a competitive edge or provide an industry step change, but an organization must be sustainable and have an architecture based on financial, ecological, and socio-technical systems. This context reconfigures the interrelationship among human and non-human actors: people and organizations, technologies and manufacturing systems, and production and consumption. Smartness expresses a new relationship between society and technology in the name of Industry 4.0 (Bauer et al., 2019; Bednar & Welch, 2020; Mazali, 2018; Rogers et al., 2019; Rossi & Di Nicolantonio, 2020; Yao et al., 2019).

The advent of Industry 4.0 has made many changes, and the concepts of design oriented to humans are not exceptional. Some concepts are defined in different contexts, and the boundaries of their application overlap and are often used interchangeably. The similarity among these concepts is a multi-objective approach that aims at designing products and/or services towards human well-being while ensuring sustainable development. In a broader sense, this multi-objective approach addresses not only human factors and ergonomics towards human diversity, but also design for manufacturability: the design process must be efficient; the manufacturing processes must be capable, proactive, and economic (Anderson, 2014; Favi et al., 2021; Sinclair, 1992). This perspective must also take the approach of life-cycle management that aims at managing the activities of products and/or services across the life cycle towards sustainability, such as life-cycle cost analysis for economics (Aurich et al., 2007; Jasiulewicz-Kaczmarek et al., 2021; Kambanou, 2020). This multi-objective approach in HCD is not only consistent with the definition of HCD reported by International Organization for Standardization (2019) (Fernandez-Carames & Fraga-Lamas, 2018; Rossi & Di Nicolantonio, 2020) but also provides a broader perspective throughout the value chain in the context of Industry 4.0.

Due to the broader perspective and diverse contexts in which the concepts regarding HCD have emerged and spread across disciplines, it would be difficult for scholars to set a proper research direction. This difficulty motivates us to review and structure lessons learnt in literature via the cross-disciplinary lens to identify coherent research directions for subsequent researchers and industrial practitioners alike. To realize our objective, the following section presents the protocol of SLR that allows the body of knowledge to be gathered in a systematic but objective way.

Research methodology

Figure 1 shows a process flow of SLR whose objective is to sufficiently cover the research topic and provide evidence with minimization of subjectivity and bias (Boell & Cecez-Kecmanovic, 2015; Tranfield et al., 2003).

First, there are two fundamental keywords, including "human-centered design" and "industry 4.0". However, scholars use disparate terms to describe the concepts, and the boundaries of these concepts remain blurred, as analysed in "Human-centred design in industry 4.0" section. Therefore, a wide range of keywords were identified and combined to discover comprehensively and objectively across a broad range of well-known databases whose description is provided by "Appendix" (Table 9): Web of Science, Scopus, Science Direct, Emerald, SpringerLink, Engineering Village, SEGA Journals, and EBSCO. Covering a wide range of substantial databases is one of the decisive efforts for overcoming the limitations of a single database, as reported by Saha et al. (2020). One problem with this breadth of databases is the noticeable difference among their search functionality that requires adjustment according to each database, as detailed by "Appendix" (Table 10).

As a result, there are 265 identified papers, and nearly 162 of them are found by the database of SpringerLink and Emerald, whose disciplines focus on varying fields—science, technology, engineering, and management—that show the transdisciplinary applications of HCD. Table 1 also shows that the number of papers found across databases decreases while that of duplicate papers among them increases proportionally, which shows that papers relevant to this research have been sufficiently covered and reached a state of saturation.

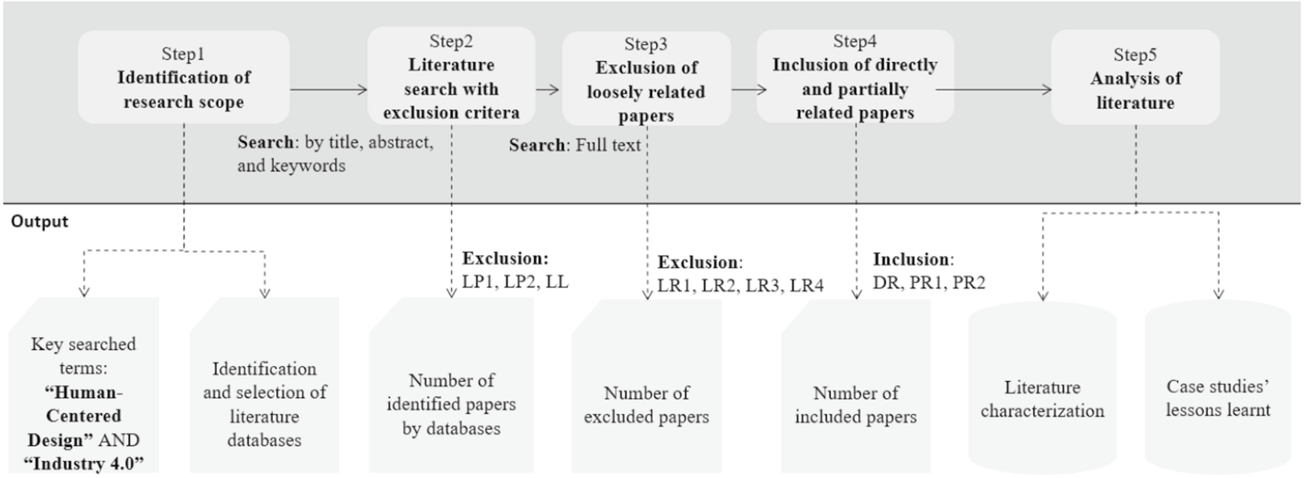

Fig. 1 A process flow of systematic literature review

Table 1 Identified papers by database

Searching database	Identified papers	Duplicate papers	Non-duplicate papers
SpringerLink	106	1	105
Emerald	56	1	55
Web of Science	14	0	14
Scopus	25	11	14
SAGE Journals	11	1	10
ScienceDirect	17	8	9
EBSCO	25	18	7
Engineering Village	11	10	1
Total	265	50	215

The next step continues with the review protocol to distinguish two groups of inclusion and three groups of exclusion criteria associated with their corresponding description, described in Table 2. In addition to the exclusion of duplicate papers (LP2), we also ensure the credibility of published papers by excluding papers that have not undergone a review process and have been published in journals (LP1).

Given our competence in the language, the papers written in non-English language (LL) are not considered for this study. To keep our research focus, we also excluded all irrelevant papers that mention HCD and Industry 4.0 as examples (LR1) instead of their main research subject; mention the research agenda (LR2) instead of research focus; or cite expressions (LR3), keywords and/or references (LR4). For instance, we found the paper published by Ribeiro and Bjorkman (2018), "Transitioning From Standard Automation Solutions to Cyber-Physical Production Systems: An Assessment of Critical Conceptual and Technical Challenges", as the search result on the database of Web of Science. However, the paper focuses on the aspects of CPSs instead of HCD, which only appeared as a reference paper. At the end of step 3, we excluded all irrelevant papers across the databases for the following step.

The included papers are analysed in detail and ranked in order according to what extent they are relevant to HCD and Industry 4.0, with a focus on the manufacturing areas. We classified them into three groups of inclusion: (DR) 24 directly related papers dedicated to HCD in the context of manufacturing; (PR1) six partially related papers studying HCD but in different contexts; (PR2) 47 partially related papers providing useful information related to HCD: design concepts, design methods, supporting technologies, human diversity, ergonomics, economics, manufacturability, and sustainability. Based on our presented objectives, the following section starts by presenting the overall characteristics of the literature, followed by an in-depth review of case studies—emerging trends, design methods, lessons learnt—and opportunities for future research.

Table 2 Inclusion and exclusion criteria

I/E	Criteria	Coded	Description	Identified papers
			Total identified papers	265
Inclusion			Total included papers	77
	Directly related	DR	An abstract indicates that the full text of the article is *directly* dedicated to HCD *and* Industry 4.0 *in* the context of manufacturing	24
	Partially related	PR1	An abstract indicates that the full text of the article is *directly* dedicated to HCD *and* Industry 4.0 *beyond* the context of manufacturing	6
		PR2	An abstract indicates HCD *and* Industry 4.0, but the full text only provides discussions on one or some aspects of HCD	47
Exclusion			Total excluded papers	188
	Loosely related	LR1	HCD *and* Industry 4.0 are only mentioned as an example	3
		LR2	HCD *and* Industry 4.0 are only mentioned as a part of its future research direction, future perspective or future requirement	5
		LR3	HCD *and* Industry 4.0 are only mentioned as a cited expression	2
		LR4	HCD *and* Industry 4.0 are only mentioned in keywords and/or references	103
	Limited publication	LP1	A paper is not published as a journal article in the studied databases	24
		LP2	A paper is duplicated on the different studied databases	50
	Limited language	LL	A full-text paper is not mainly written in English	1

Literature characterization of human-centred design in industry 4.0

This section provides an overall quantitative picture of the included papers: the trend of research interest associated with the most cited papers, the regions and countries where the papers are made, and, importantly, the transdisciplinary and multidimensional approach in HCD. Subsequently, the in-depth review of case studies presents the emerging trends among the concepts of HCD and design methods, followed by an affinity analysis that categorizes their research outcomes and limitations.

Overall characteristics

Growth rate of research interest

After excluding the duplicate papers, there are 215 remaining papers whose yearly publication data allow for the extrapolation of two interesting stages from 1997 to the middle of 2020, as portrayed by Fig. 2. First of all, one notices that the topic has gained momentum and research interest in different aspects of HCD. Secondly, for the period 2015–2019, there has been an almost consistent and healthy growth in the number of publications. Obviously, the 2020 data is still incomplete, which shows a lower number of publications than that of the previous years, because this research was carried out in the middle of the current year. Besides, we applied the Hot's trend prediction method to exponentially conjecture that the research publications could reach 108 papers by the end of 2020. However, the growth rate could be affected due to the global issue of Covid-19.

By examining only 77 included papers, Table 3 presents the most cited papers, accounting for 63% (329 out of 501 total citations). Interestingly, these top-cited papers have almost been published in recent years. This fact shows that the development of HCD has not matured yet, while the scholars have made the references to the recently published papers for new findings instead of citing the previous ones that have not been well generalized in the research community.

The top cited paper of Zheng et al. (2018) outlines future perspectives of smart manufacturing systems in which user experience is considered as one of development challenges, and transdisciplinary research is called for future research. Beyond the technical perspectives, the scholars also drew attention to social aspects. Specifically, the work of Mazali (2018) explicitly concluded that one of the key issues for the future is to design a balance between the worker being able to control the process by using their own intelligence and the automation of digital algorithms. This perspective is also agreed upon by the work of Streitz (2019), who graded the equal importance among humans and technologies in ambient intelligence to achieve the smart paradigm.

Publication origin

By taking a detailed look at 77 included papers, Fig. 3 shows that the most influential countries are accounted for by Germany (18%), followed by Italy (14%), and China (12%). In the regions, European countries have shown strong contributions in the field with 65% publications, which was reflected by several pieces of research—*Factories of Future* (European Commission, 2013) and *Platforms for CPSs*

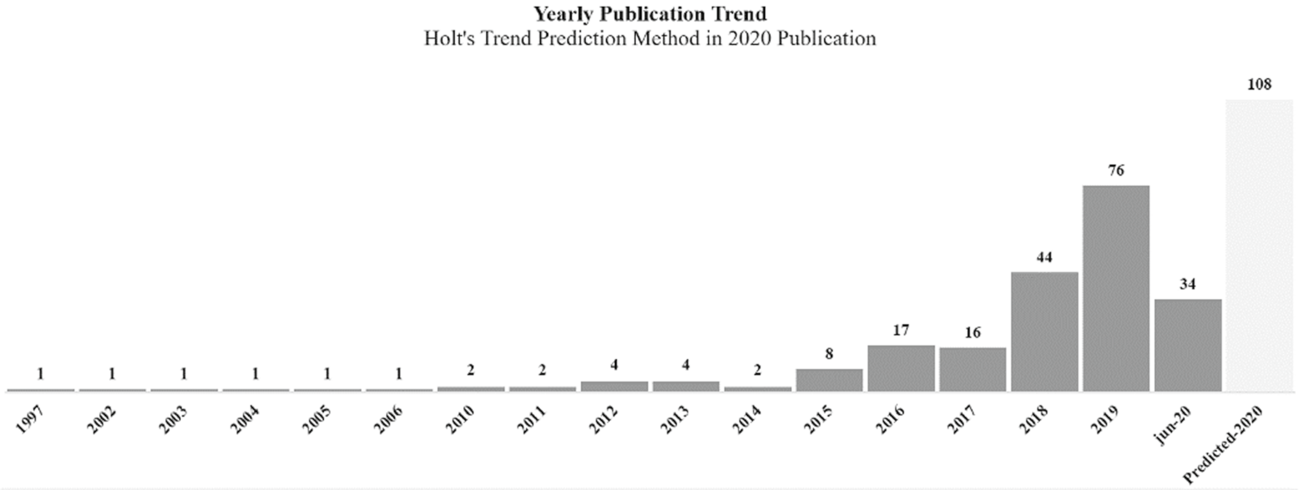

Fig. 2 Yearly publication trend with the exclusion of duplicate papers

Table 3 Papers by citations by Web of Science, retrieved from 19 July 2020

Author	Year	Paper title	Number of citations
Zheng et al. (2018)	2018	Smart manufacturing systems for Industry 4.0: conceptual framework, scenarios, and future perspectives	94
Pacaux-Lemoine et al. (2017)	2017	Designing intelligent manufacturing systems through human–machine cooperation principles: a human-centred approach	42
Brenner et al. (2014)	2014	User, use & utility research	30
Fernandez-Carames and Fraga-Lamas (2018)	2018	A review of human-centred IoT-connected smart labels for the industry 4.0	28
Lee and Abuali (2011)	2011	Innovative Product Advanced Service Systems (I-PASS): methodology, tools, and applications for dominant service design	27
Varshney and Alemzadeh (2017)	2017	On the safety of machine learning: cyber-physical systems, decision sciences, and data products	22
Streitz (2019)	2019	Beyond ‘smart-only’ cities: redefining the ‘smart-everything’ paradigm	15
Zhu et al. (2015)	2015	A product-service system using requirement analysis and knowledge management technologies	15
Mourtzis et al. (2018)	2018	Product-service system (PSS) complexity metrics within mass customization and Industry 4.0 environment	14
Leng and Jiang (2017)	2016	Granular computing–based development of service process reference models in social manufacturing contexts	14
Qin et al. (2016)	2016	Exploring barriers and opportunities in adopting crowdsourcing-based new product development in manufacturing SMEs	14
Mazali (2018)	2018	From Industry 4.0 to society 4.0, there and back	14

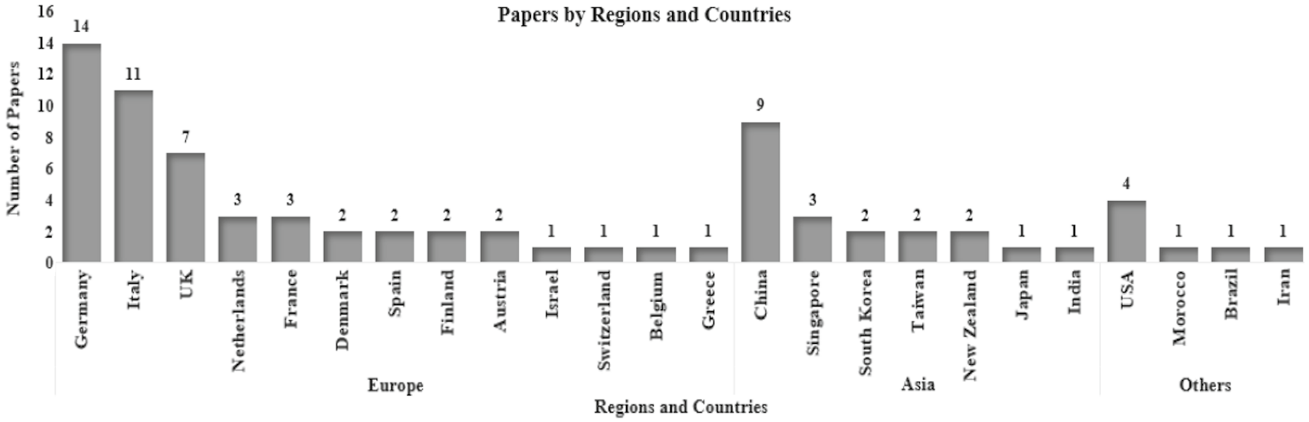

Fig. 3 Papers by regions and countries

(Thompson et al., 2018)—whose recommendation for future research indicates that it has been a long road reaching the systems of *HioTL* at the matured level together with other emerging technologies. Some specific research programs and priorities in the next three decades are extracted as below:

- Human-oriented interfaces for workers: process-oriented simulation and visualization.
- Products and work for different types of skilled and aged labour, education and training with IT support.
- Regional balance: work conditions in line with the way of life, flexible time-and-wage systems.
- Knowledge development, management and capitalisation.

Transdisciplinary approach

By examining the journals by which the included papers were published, the transdisciplinary approach of HCD is strongly evidenced by the fact that there are no journals significantly overwhelming other journals. Table 4 reveals

Table 4 Papers by journals

Journal Title	No of Papers	Category	JRC Impact factor	JRC Rank	SJR indicator	SJR rank
International Journal of Advanced Manufacturing Technology	8	Computer Science Engineering	2.633	Q3	0.999	Q1
Chinese Journal of Mechanical Engineering	6	Engineering Mechanical	1.824	Q3	0.531	Q2
Cognition, Technology & Work	3	Computer Science Philosophy Human–Computer Integration (HCI)	1.206	–	0.436	Q3
Business & Information Systems Engineering	3	Computer Science Information Systems	5.873	Q1	1.306	Q1
Journal of Manufacturing Technology Management	2	Engineering & Management	3.385	Q2	1.173	Q1
Journal of Intelligent Manufacturing	2	Computer Science Engineering	4.311	Q1	1.213	Q1
Journal of Ambient Intelligence and Humanized Computing	2	Computer Science	4.594	Q1	0.544	Q1
International Journal of Computer Integrated Manufacturing	2	Computer Science Engineering	2.861	Q2	0.658	Q2
Electronic Markets	2	Business & Management	2.891	Q2	1.006	Q2
Computers & Industrial Engineering	2	Computer Science Engineering	4.135	Q1	1.469	Q1
AI & Society	2	AI & Philosophy HCI	–	–	0.294	Q3

two interesting facts. First, the top 11 journals out of 54 journals—which publish 77 included papers—range from varying research disciplines: engineering; computer science; business management; social and philosophy, which is specialized by the journals *Cognition, Technology & Work* and *AI & SOCIETY*. This transdisciplinarity integrates cross-disciplinary perspectives—philosophy, engineering, computer, business, and social sciences—in the context of HCD and transcends their traditional boundaries. This fact addresses the interest in extending the research boundaries of various dimensions of HCD: human diversity, physical to cognitive ergonomics, economics, manufacturability, and social and human-related sustainability.

This transdisciplinary approach has also brought different studies across various research contexts, as can be seen in Fig. 4. There are 42 papers out of 77 included papers that clearly indicate their research focuses on specific manufacturing processes and industries: *machinery and equipment* as the top one, followed by *automotive industry* and *machining process*. The adaption of HCD has progressed in more specific fields: *adhesive solutions* was considered as the case study on which Lee and Abuali (2011) tested their methodology of innovative and advanced PSS; smart *labelling* design was developed from the foundation of Industry 4.0 human-centred smart label applications proposed by Fernandez-Carames and Fraga-Lamas (2018); design for *textiles* was

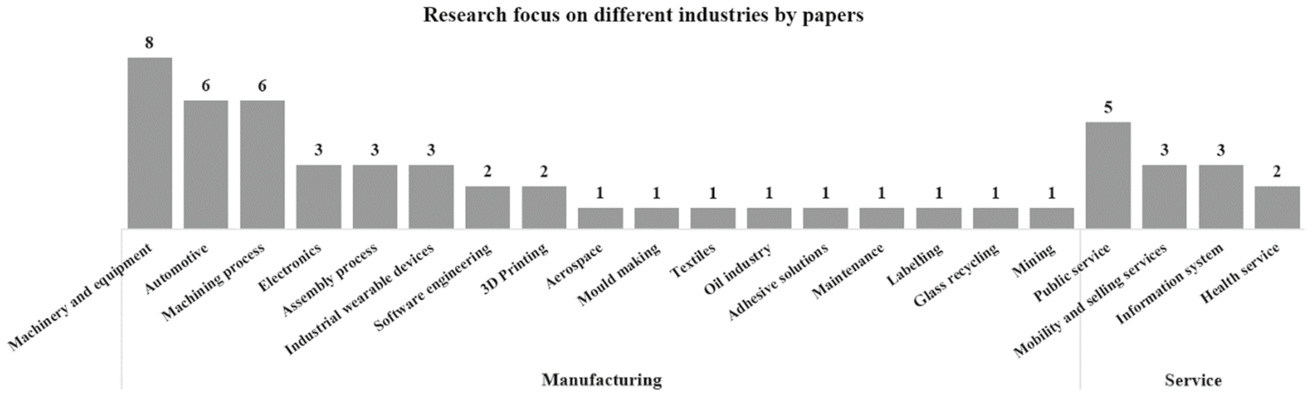

Fig. 4 Research focus on different industries by papers

implanted with interactive technologies to experiment and enhance fashion emotional design by Wang et al. (2018).

On the other hand, there are 13 papers out of 77 included papers that explicitly adapt HCD in services, for example *public service* for smart housing services—which seamlessly connect humans and machines—by design for HMI with the application of Bluetooth ubiquitous networks (Diegel et al., 2004) or a 3D-based meta-user interface (Mostafazadeh Davani et al., 2018). For the *healthcare sector*, Haber and Fargnoli (2019) emphasized the understanding of human needs and proposed the approach of PSS—the integration of products (hemodialysis devices) and services (e.g., technical support, response time)—for the offering's value. In the same sector, Gervasi et al. (2020) proposed an evaluation framework—which expresses the perspectives of engineering, cognitive, and social science—of HRC to assess the support of robots for elderly people to reach a specific place.

Multidimensional approach

The research methodology is also diverse in both conceptual and empirical research, as evidenced by Table 5. Fifty-six out of 77 included papers (around 73%) take an empirical approach, while the remaining 21 papers (around 27%) contribute to the conceptual findings. Empirical research uses scientific data or case studies for explorative, descriptive, explanatory, or measurable findings, while conceptual research focuses on abstract ideas, concepts, and theories built on literature reviews (Marczyk et al., 2005; Williams, 2011). Those conceptual papers are further categorized into SLR, accounting for four papers (around 5%) that differentiate from traditional narrative review papers (around 22%). The strong point of SLR is a replicable, scientific, and transparent process minimizing bias through exhaustive literature searches of studies and simultaneously providing the traceability of results (Boell & Cecez-Kecmanovic, 2015; Tranfield et al., 2003). Of the 56 empirical articles, 37 papers (around 66%) are qualitative studies and 19 articles (around 34%) are quantitative studies. Those figures explain the current research effort that focuses on describing, explaining, and interpreting HCD is overtaking the research effort on quantification and statistical treatment for supporting or refuting research findings. This fact is reflected by the nature of the social phenomenon being investigated from the human point of view, leading to the difficulty in the generalization of results (Mennell, 1990; Walsh et al., 2015).

Table 5 also reveals the multidimensional approach of levels of research analysis that range from the level of the product to the levels of the workstation, the company and, finally, society. The research on the level of society and the workstation is still modest in comparison with that of the company or the product, accounting for 12 papers out of 77 included papers (around 16%). The figures show there is reasonable space for further research that deals with HCD at cross-layer levels other than the company and product level, which is also consistent with the future research agenda proposed by the European Commission (2013).

In a broader sense, by applying the qualitative research methodology, Fosch-Villaronga et al. (2020) took a step beyond the company level to gather expert opinions addressing social challenges—ethical and legal issues, job availability—due to the use of social robots. They investigated the challenges from both user perspectives—privacy, autonomy, the dehumanization of interactions—and worker perspectives, such as the possible replacement of jobs by robots. Based on the companies' perspectives with regard to addressing this level of social concerns with the qualitative approach, Mazali (2018) conducted 40 in-depth interviews with managers of 20 manufacturing companies to accommodate the social needs and organizational contexts that involve multiple stakeholders and new roles of intelligent systems in workflows. In the lower area, the company level is addressed by the business cases and processes. For instance, the work of Hammer et al. (2018) shows an extension of existing business models for *quality of experience* that incorporate user needs and motivation as aspects of the individual dimension. Subsequently, the workstation level concerns the design for human-oriented workstations, for instance, addressed by Gualtieri et al. (2020) who concluded the need to perform an accurate ergonomic assessment at the first phase of workstation design. The last layer of analysis is the product level, whose design object is an artefact or a service solution.

In addition to the transdisciplinary approach—an integration of cross-disciplinary perspectives—in HCD, this

Table 5 Methodological approaches of included papers

Level of analysis	Conceptual		Empirical		Total included papers
	Systematic literature review	Traditional literature review	Qualitative	Quantitative	
Society level		3	2		5
Company level	2	8	17	5	32
Workstation level			5	2	7
Product level	2	5	14	12	33
Total	4	16	38	19	77

multidimensional approach is also evidenced by the cross-layer level—the product and/or service, workstation, company to social level—in which humans are centred.

In-depth review of case studies

There are 43 papers that report case studies out of 77 included papers (around 56%), as detailed by "the Appendix" (Table 11), which provides a useful source for researchers to make references to design for case studies. Those case studies report the design problems associated with the contexts, data collection, and analysis in both quantitative and qualitative approaches. The review objective is to make contributions to the future research agenda by harmonizing the lessons learnt that reveal the research results and limitations of the case studies. In addition, the subsequent section provides the emerging trend of concepts regarding HCD, followed by the structured harmonization of design methods.

Emerging trend

The strategy to categorize the case studies follows the design concepts embraced by the corresponding paper. Those concepts are not always explicitly indicated by the papers that may use the term "human" or "user" and even consider them interchangeable terms. This confusion is also reported by Holeman and Kane (2020) and Bazzano et al. (2017). Therefore, Table 6 structures the description of the concepts associated with their common context of use.

The variants of HCD reinforce the findings of the trans-disciplinary and multidisciplinary approach—physical to cognitive ergonomics, products and/or services to social-technical systems—towards human diversity, ergonomics, economics, manufacturability, and social and human-related sustainability. Based on the understanding, Table 7 captures the emerging trend that provides insights into six concepts summarized in chronological order.

The top three concepts—namely HCD, PSS and UCD—that account for 35 out of 43 case studies (around 81%) are the most frequently and recently used concepts during the last three years. HCD is the most popular term, although it originated somewhere in the 1400s to systematically improve design for procedures and tools to accomplish the work (Nemeth, 2004). HCD has changed dramatically in the context of Industry 4.0, where scholars have expanded the research of physical ergonomics to systems including humans. Specifically, the case studies are designed in various implementation scales in different contexts: the product level by testing the method of *individual product innovation design* in solving bicycle problems based on ergonomic perspectives (Wu et al., 2013); the company level by validating the proposed model of the *artificial self-organizing manufacturing control system* explicitly putting humans in the centre of the system design (Pacaux-Lemoine et al., 2017). Beyond technology, the trend of market personalization has received increasing attention from researchers. The literature witnesses the increasing number of case studies that pertain to the concepts of PSS and UCD. The case studies also distinguish clearly between PSS and UCD by the way that PSS focus on business models at the company level while UCD experiments focus on human experiences about design for product and/or service solutions at the product level in consideration of human diversity and social aspects.

On the other hand, the case studies related to the concepts of HioTL, HMI and HRC are not well accounted for. One of the technical challenges is that the boundaries between technologies and humans are increasingly fuzzy: language processing, social robotics, artificial intelligence, cyber physical systems, virtual reality, and augmented reality. This phenomenon is blurring the limits of where the human ends and technology starts (Frauenberger, 2019; Gervasi et al., 2020; Weichhart et al., 2019; Wojtynek et al., 2019). Moreover, recent research tends to focus on technical aspects instead of tackling existing problems related to error-prone interaction between human and non-human actors (Klumpp et al., 2019; Song et al., 2016).

Another fact shows that the research community has responded in a determined way—35 case studies during the period of 2017–2020, which greatly exceeds other periods—to the call for empirical research in the field (Benabdellah et al., 2019; Kadir et al., 2019). This effort, which is worthy of emphasis, reveals an increasing interest in empirical studies, which brings research and industrial applications closer together. This trend also aligns with the future research recommendations: *Factories of Future* (European Commission, 2013) and *Platforms for CPSs* (Thompson et al., 2018). The following deep analysis manifests the design methods connected with supporting technologies that the papers embrace in order to realize the effort in question.

Design methods

Norman (2016) explains that "the human mind is exquisitely tailored to make sense of the world" (p. 2). This ability requires products and/or services that are designed for easy interpretation and understanding. Therefore, methods for design must define procedures, techniques, aids, or tools to discover the minds of humans—users, customers, stakeholders—that serve as key inputs resulting in well-designed solutions. Figure 5 captures the frequency of design methods that are discussed in four generic groups: discovery, clean-up, engineering, and experiment.

Around 63% of case studies make the most of *iterative design*: knowledge obtained through the discovery is assured by an iterative process of idea exploration, gathering, and assessment. This method contains a bundle of

Table 6 Variants of HCD in various contexts of Industry 4.0

Design concepts	Description	Context	Authors
Human-centred design (HCD)	Applies physical, cognitive, and social factors to design—tools, tasks, machines, systems, and environments—for enhancing effectiveness and efficiency: human use and safe	General	Fernandez-Carames and Fraga-Lamas (2018), Grandi et al. (2020), Rossi and Di Nicolantonio (2020)
Human-in/on-the-loop (HioTL)	Indicates a human-in-the-loop system that requires human intervention in maintaining its continual operations; a human-on-the-loop system that shifts the human role to govern its autonomous operations	Cyber physical systems	Zhang et al. (2017), Nahavandi (2017), Kong et al. (2019), Vanderhaegen, (2019)
Human–robot collaboration (HRC)	Studies a collaborative system that achieves common goals shared by humans and robots working autonomously together to perform their assigned tasks through collaboration: knowledge sharing and social negotiations	Cyber physical systems	Richert et al. (2018), Weichhart et al. (2019), Cohen et al. (2019), Fosch-Villaronga et al. (2020), Gervasi et al. (2020)
Human–machine interface (HMI)	Defines a system's interfaces that allow humans to understand and operate it. This design embraces transdisciplinary knowledge and skills: human factors, industrial design, information processing, and cognitive psychology	Cyber physical systems	Oborski (2004), Lepratti (2006), Wu et al. (2016), Chen and Duh (2019), Ong et al. (2020)
User-centred design (UCD)	Studies an iterative design process whose research subject is not only usability but also user experience: emotional and psychological responses to interaction design	Social-technical systems	Wu et al. (2016), Kymäläinen et al. (2017), Lin (2018), Mazali (2018)
Product-service systems (PSS)	Indicates a system integration of products and services that facilitates customer-focused and co-creation models to deliver value propositions towards sustainability through all its life-cycle stages	Servitization	Grieger and Ludwig (2019), Cheah et al. (2019), Haber and Fargnoli (2019), Leoni (2019), Bednar and Welch (2020), Saha et al. (2020)

Table 7 Emerging trend of HCD concepts across case studies towards Industry 4.0

Design concepts	2005–2007	2011–2013	2014–2016	2017–2020	Total cases
Human-centred design (HCD)	1	1	1	11	14
Product-service systems (PSS)	–	1	1	11	13
User-centred design (UCD)	–	–	1	7	8
Human-in/on-the-loop (HioTL)	–	–	–	3	3
Human–machine interface (HMI)	–	–	2	1	3
Human–robot collaboration (HRC)	–	–	–	2	2
Total cases[a]	1	2	5	35	43

[a] Total cases for each concept summed from "Appendix" (Table 11)

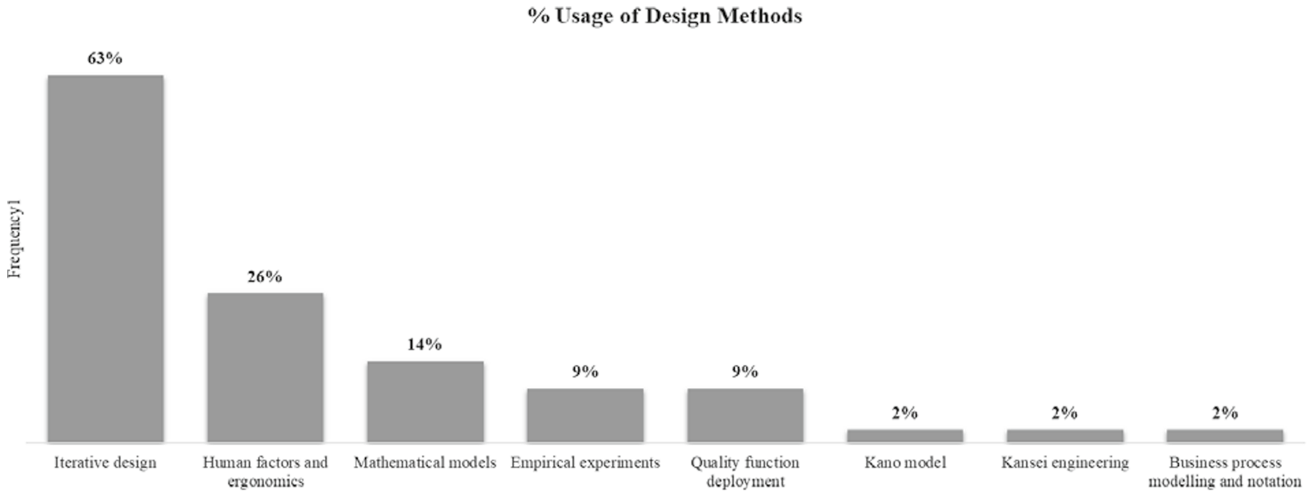

Fig. 5 Design methods applied by the reviewed case studies. [1]Frequency divided by the total number of case studies (43 case studies) derived from "Appendix" (Table 11)

procedures, techniques, and tools—participatory design, interviews, questionnaires, focus groups, scenario observation, field studies, prototyping—for searching and matching design ideas with the human mind. These approaches help designers focus on human diversity to gain critical design inputs and feedback: requirements elicitation acquired from maintenance professionals by field studies (Kaasinen et al., 2018), human perception of different stakeholders by focus groups (Turetken et al., 2019) and usage difficulties of non-expert users by scenario observation (Song et al., 2016). On the basis of questionnaires, Kong et al. (2019) also studied and called user frustration "the key pain spot" in the context of industrial wearable systems. They also pointed out countermeasures—confinable and reconfigurable modularized hardware sets—that address the usage, cognitional, and operational issues, and reduce the complexity and cost in the design solutions considering various aspects: ergonomics, plug-and-play features, and manufacturability. The modular approach is also comparable to *product platform design* that tackles the issues regarding manufacturability—product customization, variety, and commonality between products—and brings a competitive advantage: reduction in design effort and time-to-market for future generations of products (Farrell & Simpson, 2003; Martin & Ishii, 2002; Simpson, 2004). This is further evidence to show the necessity of the transdisciplinary and multidimensional approach within which an engineering method can also be applicable in the context of HCD to integrate human and non-human factors: human diversity, ergonomics, economics, manufacturability, and sustainability.

In addition to the acquisition of human needs and requirements, iterative design is also suitable for investigating "what-if" scenarios on design solutions. For instance, Kymäläinen et al. (2017) and Harwood et al. (2019) built fiction prototyping—video-illustrated and tangible interaction tools—to facilitate human-centred perception and cognition of the future potentials of products and/or services. This so-called design fiction—an interactive and tangible approach—evaluates alternative design solutions or criticizes existing ones (Knutz et al., 2014) before they are manufactured and/or delivered to customers, which enhances the robustness of iterative design by deeply understanding human experience.

Even though an effective understanding of human requirements is vital for well-designed solutions, this task is difficult due to various subjective human ideas: prioritization, complexity, imprecision, and vagueness. Clean-up is significantly more challenging for requirements of services than those of products (Haber & Fargnoli, 2019; Song & Sakao, 2016). To respond to the challenge, 6 out of 43 case studies (14%) deal with fuzzy inputs and multiple-criteria decision making by applying *mathematical models*: analytic network process (ANP), Thurstone's Law of Comparative Judgments (LCJ), fuzzy set theory, and geometric vectors. While Zhu et al. (2015) took advantage of ANP to determine and prioritize the importance weights of engineering characteristics derived from a set of different customer requirements, Haber and Fargnoli (2019) prioritized customer requirements by the LCJ that transforms the customer preferences into scale values and then represents the importance of each preference. To quantify the complexity, Mourtzis et al. (2018) proposed a 2D geometric vector to estimate the product and service's design complexity, which is defined by information content, quantification of information, and diversity of information. This quantification of complexity supports the decision-making process on alternative design solutions, taking manufacturability into account. To deal with imprecision and vagueness, Chen et al. (2016) evaluated the users' perceptual images and feelings about products by the use of the fuzzy membership degree of emotional semantic descriptive words (e.g. traditional-modern, geometrical-organic, romantic-realistic). They also used a statistical method—principal component analysis—to cluster the varying user perceptions and feelings into homogeneous groups of design characteristics. Similarly, Leng and Jiang (2017) clustered similar individual service design processes into homogeneous bundles of services by applying a granular computing method—fuzzy set theory combined with quotient space theory for classification (or clustering) of uncertain complex problem (Zhang & Zhang, 2010). Taking both customer and engineering subjective ideas, Chen (2016) carried out the fuzzy analytic hierarchy process (AHP) to develop good quality design based on the imprecise relationship between engineering experience (robust design, design optimization, design cognition) and customer experience (requirements management, ergonomics design). Based on that, the author also proposed a linear programming model to optimize the total profit of the product mix-experience portfolio, taking economic considerations into account. This cost–benefit analysis needs to be embraced because its importance is stated by several authors, especially with regard to the entire life-cycle cost analysis (Anke, 2019; Heidari et al., 2020; Rodriguez et al., 2020). These mathematical methods are useful in dealing with the multiple-criteria decision making and fuzziness (uncertainty) under their own assumptions, constraints, and computing capability, requiring practitioners to be transdisciplinary and understand properly the methods in their context of use. For references regarding these methods, refer to the work of Golden et al. (1989), Kubler et al. (2016), and Liu et al. (2020).

In addition to the discover and clean-up, 26% of the case studies apply *human factors and ergonomics* to understand and evaluate quantitatively the interactions—physical and cognitive ergonomics—among humans and other actors (e.g., design artefacts, virtual objects, system interfaces, industrial workstations) from the engineering perspective. This method is not only for the expected cost saving, but also for the higher process efficiency that can be realized by shedding light on human factors and incorporating human needs and behaviour in a healthy, safe, efficient and enjoyable manner (Labuttis, 2015; Soares & Rebelo, 2016). In the context of Industry 4.0, this method is also supported by the digital technologies—virtual and mixed reality, eye-tracking systems, digital modelling and simulation for virtual workplaces—to facilitate designers to capture and analyse design data that span from the physical to cognitive level. On the cognitive level, Wu et al. (2016) studied the relationship between interface complexity and user diversity—novice and expert (human background)—by measuring users' psycho-physiological data (eye-movement research) combined with questionnaire evaluation methods: NASA-task load index and Questionnaire for User Interface Satisfaction (QUIS) to measure operators' subjective feelings and workload throughout the experiment. These eye-movement data provide insights into the visual, cognitive, and attentional aspects of human performance (Duchowski, 2002). In addition to the psycho-physiological analysis, Richert et al. (2018) surveyed participants' personality dimensions—agreeableness, conscientiousness, neuroticism, openness to experience—to measure the performance and human perception of hybrid human–robot collaboration. On the physical level, Caputo et al. (2019) carried out an appraisal for the human-centred workplace design by reproducing a virtual workplace in which digital human modelling simulates the whole human task towards preventive ergonomics. Peruzzini et al. (2019) also designed the virtual workstation with preventive ergonomics by the use of digital technologies: virtual and mixed reality. They also used questionnaire methods to quantitatively measure postural comfort: Rapid Upper Limb Assessment (RULA) and Ovako Working Posture Analysis System (OWAS). The case studies apply a wide range of assessment methods regarding human factors and ergonomics: from simple checklists to more complex techniques; from physical ergonomics—for human use and performance (e.g., musculoskeletal symptoms, body posture, low back disorders)—to cognitive ergonomics—for human perception and cognition (e.g., mental stress, emotional stress, situation awareness). In addition, the work of Tillman et al. (2016), Forsythe et al. (2017) and Dalle Mura and

Dini (2019) provides a good source of numerous methods for human factors and ergonomics that allow for achieving the various objectives of both manufacturability and social sustainability.

To bridge the gap between human requirements and engineering characteristics, four out of the 43 case studies apply *quality function deployment* (QFD), which originated in the automotive industry and has been being used with different applications in diverse fields for five decades (Kowalska et al., 2018; Zairi & Youssef, 1995). This method identifies human-centred requirements, classifies the importance of those requirements, defines engineering characteristics that may meet those requirements, allows for verification of design conflicts among them, and then prioritizes design solutions. In the analysed case studies, this method is also integrated with different methods—application space map and innovation matrix (Lee & Abuali, 2011), ANP (Zhu et al., 2015); AHP, fuzzy AHP, entropy weight method (Ma et al., 2017); LCJ and Kano model (Haber & Fargnoli, 2019)—to enrich the prioritization and segmentation of the design requirements. The requirements after the cleanup are further converted into the engineering parameters by the QFD. For further reading, the work of Chan and Wu (2002) and Prasad (1998) may be of interest to the reader.

Furthermore, other methods also include the *Kano model*, *Kansei engineering*, *business process modelling, and notation* (BPMN). While Haber and Fargnoli (2019) applied the Kano model to prioritize and classify customer requirements into four different categories—must-be, one-dimensional, attractive, indifferent—for the segmentation of customer value propositions, Wang et al. (2018) parametrically linked the customer's emotional responses—physical and psychological—to the properties and characteristics of a product and/or service. If these methods focus on a particular process in design (requirement elicitation converted into engineering characteristics), Prinz et al. (2019) highlighted the use of BPMN to represent workflows—a graphical modelling language for all kinds of business processes. The BPMN is useful for examining a graphical description of design processes to different levels of granularity and discovering inconsistencies and/or differences in sequential steps, conflicting names, or acronyms, to name a few. Even though the methods have only been mentioned one time by the 43 case studies, they have been adapted and applied by different fields for years. Several publications are interesting works that may help readers have a better idea about the Kano model published by Zhao et al. (2020) and Shahin et al. (2013), Kansei engineering reviewed by Shiizuka and Hashizume (2011) and Coronado et al. (2020), BPMN studied by Ko et al. (2009) and Chinosi and Trombetta (2012).

Lastly, another way of gaining knowledge in design is *empirical experiments*, which account for four out of the 43 case studies. This method is useful for understanding what-if scenarios by different design configurations: an assisted versus collaborative robotic system that supports workers in a plug-and-produce workstation (Wojtynek et al., 2019), an automatic speed versus adaptive cruise control system for pedagogical learning supports (Vanderhaegen, 2019), delivery of health care services for seniors between a community hospital and social service agency (Hoe, 2019), augmented reality that supports trainers versus trainees in phone repairing operations (van Lopik et al., 2020). Those empirical experiments allow for designing hypotheses and gaining knowledge by means of direct and indirect experience. However, this method requires knowledge of the experimental setup and validation; it also has limited generalization of results due to controlled settings (Kulyk et al., 2007).

In summary, the case studies apply various methods that are categorized in the four generic groups—discovery, clean-up, engineering, experiment—associated with supporting technologies to tackle different problems, which requires the transdisciplinary approach for understanding and applying the methods in their proper context of use. While iterative design is power in discovering the human mind (needs, perception, cognition), mathematical models prioritize and classify those human inputs and support the decision-making process on design alternatives. Furthermore, human factors and ergonomics enrich the understanding of interactions—physical to cognitive ergonomics—among human and non-human actors with the support of digital technologies: virtual and mixed reality, eye-tracking systems, digital modelling and simulation for virtual workplaces. To convert the voice of humans into engineering parameters, the case studies have diverse approaches—QFD, Kano model, Kansei engineering, BPMN—and are used in different combinations. Finally, the empirical experiments gain knowledge based on the investigation of what-if scenarios under the human perspective, which is useful for iteratively improving and testing design solutions. Besides, researchers and practitioners alike also benefit from other relevant engineering methods—product platform design (Simpson et al., 2014), design for manufacturability and concurrent manufacturing (Anderson, 2014), to name a few—that embrace the transdisciplinary and multidimensional approach to deal with a multi-objective design problem towards human diversity, ergonomics, economics, manufacturability, and sustainability.

These various methods dealing with different problems in diverse contexts of use lead to different lessons learnt in the form of their research results and limitations. The following lessons learnt are useful for subsequent researchers to choose proper research areas and advance research contributions to the field by avoiding the research limitations.

Lessons learnt

One way to organize the case studies sharing mutual facts and document them as the lessons learnt is to use an *affinity analysis,* which is also known as the *KJ method* and applied in various fields (Awasthi & Chauhan, 2012). The information captured during the analysis is tabulated by "Appendix" (Table 11), providing researchers useful details about design for case studies. Based on the analysis output, Table 8 categorizes the case studies' results and limitations into six groups of research results (RR) and four groups of result limitations (RL).

One of the most attractive outcomes those case studies reported is the exploration of the design success factors—which are denoted as RR2 accounting for around 47% of the case studies—revealing how the successful deployment of design oriented to humans can be generalized in various contexts. Figure 6 structures those success factors as a triangular decision-making diagram:

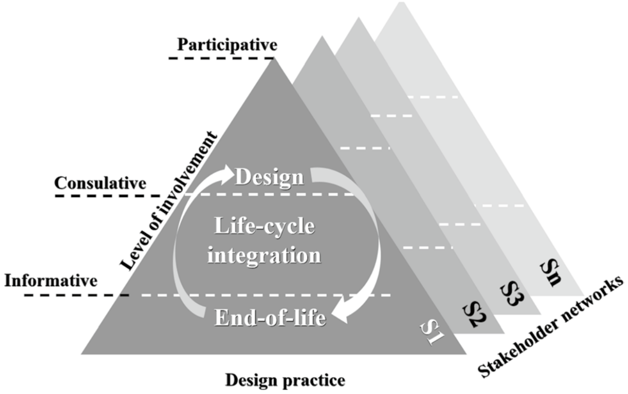

Fig. 6 A triangular decision-making diagram in HCD, encompassing design decisions on who in the stakeholder networks (S1, S2, S3, Sn) will be involved, at what levels of involvement, where the involvement will take place in each through-life phase, and what design knowledge should be exploited within the scale of physical to cognitive ergonomics

- *Stakeholder networks*: the organizational, social, and environmental contexts—which involve stakeholders (e.g., users, customers, employees, suppliers, distributors, partners, regulators, etc.) through the life-cycle design process—are essential for enhancing the credibility of information and promoting the sharing of transdisciplinary knowledge as valuable design inputs (Chen, 2016; Mazali, 2018; Schulze et al., 2005; Witschel et al., 2019). The diversity in interests and expectations of the stakeholders needs to be respected and analysed to comprehend the impact of stakeholder interactions and their features at different life-cycle design phases: design, production, delivery, service, maintenance and end-of-life cycle (Mourtzis et al., 2018; Turetken et al., 2019; Zhang et al., 2020). In this respect, the involvement of the users or customers in the early development stage is well realized (Chen et al., 2016; Grieger & Ludwig, 2019; Hoe, 2019).
- *Levels of involvement*: the engagement modes of stakeholders are depicted by three levels of involvement. These levels include the informative level in which stakeholders only provide and receive design information; the consultative level in which they comment on pre-defined design scenarios; and the participative level in which they make influencing decisions on a design process, which is a higher level of engagement than that of the informative level, which only considers stakeholders as information sources in the design process (Schulze et al., 2005; van Lopik et al., 2020).
- *Design practice*: the design development—which responds to the extents to which the data about users, customers, and other relevant stakeholders should be properly obtained and analysed—needs to be defined. These data include physical activities, behaviours, opinions, feelings, personalities, and physiological responses (Lin, 2018; Peruzzini et al., 2019; Richert et al., 2018; Wang et al., 2018). They are explicitly classified into two groups: physical ergonomics—which emphasizes physical characteristics—and cognitive ergonomics, which reflects the integration of cognition thinking and cultural

Table 8 Results and limitations of research case studies in literature

%^{a}	RR codes	RR description	RL description	RL codes	%^{a}
47	RR2	Explored design success factors	Limited statistical power in result validation	RL1	60
23	RR1	Achieved engineering objectives of design	Lack of generalizability of results	RL2	56
23	RR6	Provided supporting design frameworks	Require supporting methods to facilitate the implementation of proposed models	RL4	30
12	RR3	Validated the effect of human diversity	Lack of validation on effectiveness of the proposed solutions	RL3	23
9	RR5	Provided transdisciplinary frameworks			
7	RR4	Visualized design scenarios			

[a] Frequency divided by the total number of case studies (43 case studies) derived from "Appendix" (Table 11)

characteristics—individual aesthetic habits, national, ethnic cultural differences—to address social-technical aspects in the context of Industry 4.0 (Bednar & Welch, 2020; Fosch-Villaronga et al., 2020; Zhou et al., 2012).

The knowledge management of these design data is well expressed as an enabling success factor that can be exploited by digital technologies. These technologies facilitate the collection, organization, retrieval, and reuse of design knowledge in an effective manner. While Fu et al. (2019) took advantage of IoT solutions (sensors) for user data collection—unintentional behaviour, emotion, culture—and artificial intelligence for data processing, Vanderhaegen (2019) and Grandi et al. (2020) made use of digital and mixed reality simulation in measuring human factors—physical stress, physiological data—and evaluating their design experiments. Instead of starting from scratch, Zhu et al. (2015) and Leng and Jiang (2017) established mathematically a collection of semantic commonalities derived from historical design ontology-based databases—activities, functions, concepts, process sequences—to build a knowledge platform from which a stream of new derivative products and services can be efficiently developed. The objective is to design for variety and custom solutions, enabling designers to not only save time and cost but also make the most of the experience and expertise that were dedicated to the past design activities. The method used to build the knowledge platform is also comparable with product platform design, which has been maturely researched over the last decade (Simpson et al., 2006, 2014) and is a useful source regarding methods and applications for researchers in the field of product and/or service design.

The second group is the engineering objectives of design (RR1) that are converted into key performance indicators to quantify the effectiveness of the proposed models or frameworks. Around 23% of the case studies indicate that their proposed solutions achieve the engineering objectives: avoidance of ergonomic risks (Caputo et al., 2019; Ceccacci et al., 2019), improvement of productivity and simultaneously biomechanical workloads (Gualtieri et al., 2020; Wojtynek et al., 2019), production performance in terms of quality and engineering time (Pacaux-Lemoine et al., 2017; Prinz et al., 2019). Furthermore, Wu et al. (2013) proposed a multi-function and modular method for design focusing on human anthropometrics—the branch of ergonomics that deals with measurements of the physical characteristics of human beings (Pheasant, 1990)—and extending products' service life towards sustainability. Similarity, Chen et al. (2016) applied a clustering method for product family design based on anthropology—research in understanding human culture, society, and difference (Monaghan & Just, 2000)—to improve the agility of the design process towards manufacturability. This product family design allows designers to not only utilize existing design methods from the product platform to form a series of products, but also gain inspiration from different ethnic groups—human diversity with distinct cultural traits—to extract ideal design elements. In another aspect, Chen (2016) emphasized directly the cost–benefit analysis of design quality, taking into account two economic elements: estimated profit; total cost comprising R&D cost, market capital, and design quality for market share. The reported figures prove the robustness and performance of a system—human diversity, ergonomics, economics, manufacturability, sustainability—can be achievable with the approaches of HCD.

The next research interest is to provide supporting design frameworks (RR6) that facilitate the design process by providing systematic thinking—the use of the integrated novel design methods (innovation matrix, application space mapping, QFD) and Lean initiatives (avoidance of valueless reworks and activities)—towards economic sustainability (Lee & Abuali, 2011; Pezzotta et al., 2018). Other studies focus on design solutions for complexity and uncertainty: incomplete information regarding human requirements (Haber & Fargnoli, 2019); the changes in human preferences (Lin, 2018); decision making on different design alternatives for mass customization towards manufacturability (Mourtzis et al., 2018); interaction requirements among non-human—smart manufacturing devices/tools, core enterprise business systems (ERP, SAP)—and human actors (manufacturers, designers, users) (Mostafazadeh Davani et al., 2018; Song et al., 2016; Zhang et al., 2020); adaptation of design processes to the context of small-and medium-sized enterprises (Adrodegari & Saccani, 2020; van Lopik et al., 2020). These studies tackle different problems scattered across lifecycle design phases, useful to consider in relation to further research to address the relevant problems in a comprehensive way.

Around 12% of the case studies made an effort to validate the effect of human diversity on the design outcomes (RR3). They concluded with the important inclusions of individual differences—background, age, gender, education, cultural influences, privacy management—in design. Statistically, Wu et al. (2016) confirmed that information overload in interface design increased cognitive workload for novice operators compared to expert operators and therefore decreased user efficiency. Similarly, Van Acker et al. (2020) concluded statistically that higher acceptability of wearable mental workload monitoring was associated with being a woman (for trust in the technology), higher technology readiness—the willingness to accept new technologies and security about private data (Victorino et al., 2009)—and lower educational backgrounds. Besides, lack of considerations regarding specific classes of difference between humans leads to major effects on design outcomes in various design contexts: age with older people (aged 55–75 years) in safe driving (Jung et al., 2017) and health sector (Hoe, 2019); cultural influences (Russians, a Frenchman, a Chinese) in the experiment of long-term isolation in a limited room space (Boy, 2018). These studies address the concern that if design does appreciate individual differences towards the multidimensional approach—considering not only product and/or service design but also social aspects—this could avoid the thwarting of all research efforts and the subsequent lessening of potential benefits.

In addition to the multidimensional approach, four studies also directly address the need for collaborative design frameworks (RR5): the transdisciplinary approach during the life-cycle design phases. Ma et al. (2017) exploited common expertise of transdisciplinary teams to convert customer requirements into semantic requirement groups that were subsequently transferred into product design specifications through the use of QFD. Based on the perspective of cross-cutting collaboration for advanced business intelligence, Kong et al. (2019) structured a common platform design of wearable-enabled applications with three aspects of manufacturability: re-configurability, robust architecture, and design scalability. This platform allows standardization by taking advantage of plug-and-play features and modular approaches to integrate human and non-human actors: artificial intelligence, virtual reality, IoT, cloud computing, and cloud-based cyber systems (enterprise resource planning, manufacturing execution systems, warehouse management systems). In addition to manufacturability, Anke (2019) and Turetken et al. (2019) addressed directly the aspects of life-cycle cost analysis in the context of smart services. Specifically, Anke (2019) assessed the profitability of a smart service at an early stage of service design by developing a web-based tool prototype by which project teams from different disciplines collaborate in the design and evaluation process. In a broader sense, Turetken et al. (2019) promoted the transdisciplinary and iterative approach in which a network of actors—providers, customers, authorities, retailers, event organizers—co-creates the value-in-use for customers and generates benefits—financial and non-financial characters—for all network partners moving towards sustainability. Each study focuses on an important aspect of design—human diversity, ergonomics, economics, manufacturability, sustainability—that needs to be considered together in a transdisciplinary and multidimensional approach for future research.

In the last group of research interest, three studies present experience-driven approaches that visualize design scenarios (RR4) regarding future possibilities to exploit human experience. Based on design fiction, both Kymäläinen et al. (2017) and Harwood et al. (2019) demonstrated the usefulness of the video-illustrated prototype in avoiding the difficulty of interpreting abstract verbal descriptions of new design. This method enables designers to interactively envisage a spectrum of "what if" scenarios towards human experience that may then be explored by using the range of other design methods: focus groups, interviews, and questionnaires. Besides, Kaasinen et al. (2018) made the most of the technologies in Industry 4.0—wearable technologies, virtual and augmented reality—to visualize the human experience of future maintenance work: feeling competent, feeling connected to the work community, feeling a sense of success and achievement by performing better in jobs. These studies go beyond technical design towards the multidimensional approach: they go from the technical to the social aspects.

Even though all case studies reported positive outcomes, four groups of result limitations are also acknowledged. The most frequently reported limitation is the lack of statistical power in result validation (RL1)—accounting for 60% of total analysed case studies—and the rest is undefined due to limited information for making the conclusion. The lack of statistical power shows limitations in experimental set-up conditions: low sample sizes, lack of fitting in target participants, lack of sound statistical studies, and other biased experimental aspects (Pacaux-Lemoine et al., 2017; Richert et al., 2018; van Lopik et al., 2020). This limitation is followed by the lack of generalizability (RL2) showing the insufficient evidence of the extent to which findings from one study in one context can be applied and reproduced to other contexts. Specifically, 56% of the case studies are constrained and required to be tested by further quantitative methods to prove the transferability of their observed results to other usage contexts (Adrodegari & Saccani, 2020; Haber & Fargnoli, 2019; Kong et al., 2019; Witschel et al., 2019). The next limitation is categorized as incomplete solutions to implement the proposed models (RL4)—accounting for around 30% of the case studies—claiming the quality of the proposed models will depend on other external factors. These factors include the "manual" processing of the proposed models, resulting in application difficulties (Ceccacci et al., 2019; Zhang et al., 2020), which requires additional efforts in further development of supplementary methods and applications to achieve model completion in real contexts (Grieger & Ludwig, 2019; Leng & Jiang, 2017; Lin, 2018; Peruzzini et al., 2019). Finally, around 23% of the case studies do not explicitly provide the validation of effectiveness of the proposed solutions (RL3), which emphasizes the need for future research for their validation in various contexts of usage; otherwise, the practical effectiveness of the proposed solutions from the studies is limited (Ceccacci et al., 2019; Haber & Fargnoli, 2019; Witschel et al., 2019).

These limitations are explained through the evaluation methods—which are different from the design methods used as procedures or processes for attaining research findings—applied by the case studies to validate their corresponding research findings. Figure 7, which is visualized from the detailed data of "Appendix" (Table 11), shows the top four

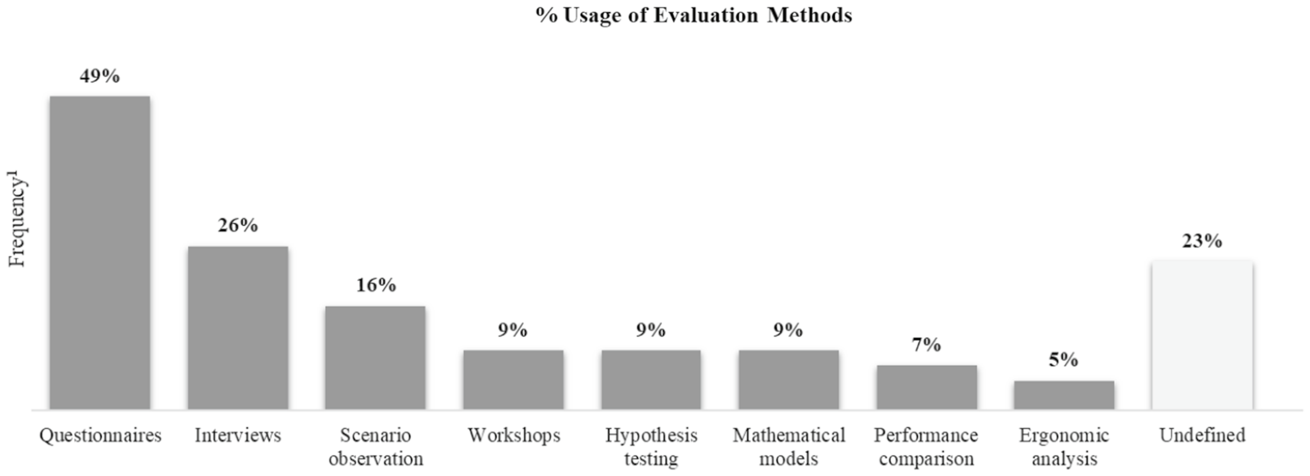

Fig. 7 Evaluation methods applied by the case studies reviewed. [1]Frequency divided by the total number of case studies (43 case studies) derived from "Appendix" (Table 11)

evaluation methods accounted by qualitative methods: questionnaires, interviews, scenario observation, and workshops. These methods validate the effectiveness of the corresponding proposed models by capturing and communicating the participants' feedback via different means, leading to a potential lack of robustness in research and encompassing subjectivity and bias in research conclusions (Jung et al., 2017; Richert et al., 2018; Van Acker et al., 2020), which is followed by insufficient generalizability, as analysed above.

Although there is a small portion of case studies applying quantitative methods—hypothesis testing and mathematical models (around 9%), performance comparison (around 7%), and ergonomic analysis (5%)—the validation of the case studies' findings is still questionable. Specifically, by applying the hypothesis testing, L. Wu et al. (2016) made an effort to carry out a case study of eye tracking with 38 participants that compared three levels of interface complexity in LED manufacturing systems, resulting in the statistical conclusion of interface complexity and user background affecting the user experience. However, the study failed to prove sufficient statistical power, showing its proper selection of sample size. Moreover, the sampling procedure included only the participants who were all from the same company, leading to biased results and affecting the generalizability of research outcomes. Out of 43 case studies, Ceccacci et al. (2019) and Gualtieri et al. (2020) conducted ergonomic analysis to validate the effectiveness of their workstation design—productivity, human postural comfort—with a sample size of only two participants. This small sample size, due to its lack of generalizability, requires further research to validate the studies' applicability in a real context with human diversity. This problem was further evidenced by Van Acker et al. (2020) who reported that, statistically speaking, the replication of their case study's findings found in the first experiment was not successful in the second experiment carried out within the same research context, so leaving the conclusion inconclusive. These limitations lead to a lack of robustness in research findings and reduce applications of these studies in industry and research alike.

In summary, the research efforts contributing to the realisation of human roles in Industry 4.0 span six groups of research results: exploration of design success factors, achievement of engineering objectives, provision of supporting design frameworks, validation of the effect of human diversity on design, provision of transdisciplinary frameworks, and visualization of design scenarios. Each study focuses partially on its own defined aspects, which provides a useful reference for future research that combines the transdisciplinary and multidimensional approach towards human diversity, ergonomics, economics, manufacturability, and sustainability in a comprehensive way. Besides, it is worth realizing the lessons learnt in order to overcome the acknowledged limitations—limited statistical power in result validation, lack of generalizability of research findings, further requirements for the supporting methods, lack of validation of the effectiveness—and enhance the robustness of the research findings. This will inspire research applications to both industry and research. Finally, the following section discusses the results of the in-depth review and ends with future research opportunities.

Discussion and opportunities for future research

The analysis of the overall characteristics of the literature regarding HCD reveals its nature and evolution towards Industry 4.0. Various disciplines have made efforts to integrate human roles into the design process, spreading extensively from artefact and service designs to system designs, taking social manufacturing contexts in Industry 4.0 into account. The topic has gained clear momentum, and interest in different concepts of HCD has increased exponentially. This phenomenon leads to evidence of evolution in HCD, whose characteristics and contextual variants—HCD, PSS, UCD, HMI, HioTL, HRC—have evolved in different disciplines across the value chain to tackle new requirements of Industry 4.0. Specifically, HCD is not only applied for the design of procedures or tools to accomplish a task but is also required to have a transdisciplinary approach. This approach ranges from physical ergonomics—for effective and safe human use—to cognitive ergonomics—for treating personality styles. Another piece of evidence is the multidimensional approach of HCD, whose unit analysis originates from design for the product and/or service level to the workstation and company level, and extends to the level of society: ethical, legal and social concerns have risen along with Industry 4.0. However, concerning the industrial state of the art in this topic, there is a lack of evidence of research with full-scale real implementations that go into any detail on cross-level designs that range from the artefact to the social level from which human issues—privacy, ethnic cultural differences, personality styles—are taken into account within transdisciplinary and multidimensional design thinking. Although an increasing number of studies integrate humans in smart manufacturing, many of them limit research scope to physical ergonomics: human factors and ergonomics on operational levels (Kadir et al., 2019; Pacaux-Lemoine et al., 2017; Peruzzini et al., 2019; Wojtynek et al., 2019). Therefore, future research needs to pay attention to the transdisciplinary and multidimensional approach.

Moreover, the changes that trigger Industry 4.0 have impacted throughout the value chain in which the human roles have been shaped in the different phases of the value chain, requiring new approaches to integrate humans in the cycle. This phenomenon also leads to the different variants of HCD as an evolution evidenced by the in-depth review of case studies. Those concepts have been widely studied in recent years, and there is no clear evidence for their maturity, which is further emphasized by the number of conceptual and empirical papers associated with the case studies found in the literature review. In particular, the terms HCD, PSS and UCD have received the most attention in the literature, showing their emerging trend of catching up with the challenges of dynamic environments and diverse changes in the design requirements aimed at personalization and sustainability. To realize the full potential of smart manufacturing, however, the other concepts of HioTL, HMI, and HRC also deserve more attention not only in conceptual research but also in empirical experiments. This is a good indication for both industry and research to pay attention to the numerous research efforts in exploring the various concepts of HCD to tackle the challenging requirements of industry 4.0. In this respect, an interesting consideration for future research would be to try to better unify the relationships between those concepts in order to embed them completely into the cornerstone of Industry 4.0 infrastructure.

In addition, the challenges in Industry 4.0 also call for diverse design methods that tackle different problems across the life-cycle design phases in the transdisciplinary and multidimensional approach. To respond to the call, the in-depth review of case studies captures a wide range of design methods categorized into four generic groups—discovery, clean-up, engineering, and experiment—associated with supporting technologies. While the discovery makes the most of the iterative design—participatory design, interviews, questionnaires, focus groups, scenario observation, field studies, prototyping—to discover human needs and requirements, the clean-up encompasses the mathematical models—ANP, LCJ, fuzzy set theory, geometric vectors—to classify and prioritize the design requirements and make multiple-criteria decisions on design alternatives. Subsequently, the group of engineering methods—human factors and ergonomics, QFD, Kano model, Kansei engineering, BPMN—converts the requirements into engineering characteristics and establishes the design process flow to centre design on humans. Lastly, the case studies carry out the experimental setups for understanding what-if scenarios by different design configurations, which is useful for iteratively improving and testing design solutions from the human perspective. Besides, the support of digital technologies—virtual and mixed reality, eye-tracking systems, digital modelling and simulation for virtual workplaces—enables designers to capture and analyse design data in an efficient way. Due to varying methods in design, it is helpful for researchers and practitioners who are transdisciplinary and understand properly the methods in their context of use. In addition to the design methods, some other engineering methods available in the literature—product design platform (Simpson, 2004), mathematical multi-objective models taking human factors and ergonomics into account (Dalle Mura & Dini, 2019)—are also worthwhile complementing the design toolkit for both products and/or services to acquire multiple design objectives—human diversity, ergonomics, economics, manufacturability, and sustainability—through the transdisciplinary and multidimensional approach in HCD.

Furthermore, the literature review also provides the detailed and useful information extracted from the analysed case studies in the subsection *lessons learnt*, showing the diverse applications of these concepts in different industrial contexts associated with the insights they provide. These lessons learnt to represent various research results associated with limitations that are captured and harmonized in homogeneous groups: six groups of research results and four groups of research limitations. Given the results, the design success factors—which are again reflected by the transdisciplinary and multidimensional characteristics—are the proper design decisions: the stakeholder networks; levels of involvement of each stakeholder at each design life-cycle phase; how deep analysis of design will take place, ranging from physical ergonomics to cognitive levels in the context of use directed to Industry 4.0. Future research needs to express these success factors that deserve attention and emphasis in a comprehensive way to avoid research limitations and market failures in industry.

Another enabling success factor is the knowledge management of design data. The digital technologies—IoT, artificial intelligent, virtual and mixed reality—facilitate the design knowledge to be collected, organized, retrieved, and reused in an effective manner. This advantage in Industry 4.0 enables designers to facilitate the multidimensional approach in the design knowledge that ranges from physical stress, to physiological data, to social data: culture, human behaviour, emotion, and background. In addition to the technology, a well-established method to construct and manage design knowledge is worth considering in future research. The useful method in this case is to establish a knowledge platform that defines a collection of semantic commonalities derived from historical design ontology-based databases. This platform design enables a new stream of products and/or services to be developed in an efficient manner towards economics and manufacturability: design for variety and customization, the use of the existing design experience, and expertise that reduces design efforts and enhances collaborative working.

In addition to the success factors, 10 out of 43 case studies provide quantifiable outcomes. These results prove that the robustness and performance of the systems can be achieved with the applications of HCD in different aspects: human diversity, ergonomics, economics, manufacturability, and sustainability. A limited array of studies incorporates human diversity—human culture, society, background—to improve robustness and sustainability—which combine the human difference with the extended service life—of design solutions. In contrast, numerous studies enhance the robustness in human performance by ergonomics: avoidance of workplace risks and reduction in biomechanical workloads. This outcome also improves economics and manufacturability in terms of production performance: productivity, engineering time, and quality. Moreover, the engineering methods—design for product platform and family, design for multi-functionality and modularity alike—seek a common design platform that paves the way for manufacturability and economics: reduction in design effort, time-to-market for future generations of products and/or services. Beyond the engineering methods, future research needs to embrace the financial perspective to quantify and evaluate the economics of HCD, such as the cost–benefit analysis that can also be extended to the life-cycle cost analysis. However, each study limits its research scope in one of these aspects, which provides a pivotal research space for subsequent researchers, who should grasp these aspects in their research of HCD within a comprehensive approach. Besides, the rest of the case studies provide limited information about how their design proposals are effective in quantifiable ways, creating a need for future quantitative research rather than the qualitative approach. Regarding this research opportunity, it is also useful to make contributions to the creation of a design evaluation system oriented to the process of HCD. This design evaluation system has the following ultimate objectives: to evaluate how well the decisions and activities that are made during the design phases actually turn out, to monitor the design process, and to facilitate decision making on any potential breakdowns and pitfalls.

Other research efforts provide the design frameworks in different contexts of use: the supporting design frameworks that facilitate the design process in an effective manner and the collaborative design frameworks that promote the transdisciplinary and multidimensional approach. The former provides systematic design thinking—integrated design methods to avoid valueless reworks and activities towards economic sustainability—and possible ways to tackle different challenges—the complexity and uncertainty in the relationship between human and non-human actors—scattered across life-cycle design phases. The latter unfolds the common expertise of transdisciplinary teams to co-create value-in-use for customers and also generate benefits—financial and non-financial measures—for all network partners towards sustainability. These frameworks reflect perspectives of the common platform design and life-cycle cost analysis, which are useful considerations for future research to contribute to multi-objective HCD in a comprehensive way.

The minority of case studies have paid attention to experience-driven design with visualization techniques: design fiction with the video-illustrated prototype, and virtual and augmented reality. These case studies give inspirational examples of how digital technologies enrich the human experience, rather than physical real prototypes that are difficult to produce or interpret in abstract verbal descriptions. This approach examines future possibilities of new design that allow designers to comprehend the human experience and go beyond technical design towards the multidimensional approach, from technical to social aspects. In this respect, another interesting research domain would be exploring the possibility of making the best of the technologies in the age of Industry

4.0 to support the process of HCD. This direction of future research would be beneficial to fulfilling the limitations—namely RL4 in Table 8—that express different concerns: computational capability (Ceccacci et al., 2019; Chen et al., 2016; Leng & Jiang, 2017), data synchronisation (Lin, 2018; Peruzzini et al., 2019), and knowledge management (Fu et al., 2019; Grandi et al., 2020; Vanderhaegen, 2019; Zhu et al., 2015).

A limited range of studies put the perspective of human diversity towards the multidimensional approach that considers not only design artefacts but also the social aspects—background, age, gender, education, cultural influences, privacy management—in design. Lack of consideration of the difference between humans could thwart all research efforts and lessen potential benefits. This is particularly true in the context of population aging, which makes human diversity an essential consideration across diverse fields (Ahmadpour et al., 2019; Dankl, 2017; Lee & Coughlin, 2015). This phenomenon challenges manufacturing design in Industry 4.0, requiring a multi-objective methodology to capture diverse human factors. For example, Dalle Mura and Dini (2019) optimized ergonomics in assembly lines by proposing a multi-objective genetic algorithm capturing human factors: age, gender, weight, height, and skill. However, Katiraee et al. (2019) indicated that human differences regarding age and skill have been well studied in the literature, while few studies investigate other human aspects, including cognitive abilities. Therefore, future research on the topic should be ready to accommodate individualization in accordance with human diversity to encapsulate a new relationship between society and technology in the context of Industry 4.0.

Last but not least, the robustness of the research findings could be jeopardized if the identified limitations could not be alleviated. The majority of identified limitations are assigned to the experimental set-up conditions: low sample sizes, lack of fitting in target participants, lack of sound statistical studies, and other biased experimental aspects. There is also insufficient evidence of the extent to which these findings in one context can be applied and reproduced in other contexts. Future research would be trying to establish and enhance the robustness of research results by satisfying certain criteria for validity, such as the use of multiple sources of evidence, replication logic in multiple-case studies, and the well-established protocol of design for case study (Isaksson et al., 2020; Voss et al., 2002).

Throughout the value chain, the impact and increasing challenges of the transition to Industry 4.0 mean that integrating the role of humans is a part of the transition. It is going to attract more and more research efforts for the next decade, at least in the following five years. This is an opportunity to look back in a systematic manner on what the literature has achieved and the lessons it's learnt, as summarized in the following points for the considerations of future research:

- *Research approach*: The fulfilment of the transdisciplinary and multidimensional HCD needs to be achieved through a systematic identification of stakeholder networks, levels of their involvement in each life-cycle design process, and design practice.
- *Research scalability and robustness*: The proposals of a design methodology should provide well-proven empirical results in well-validated case studies in varied contexts in which the individualization towards human diversity is taken into account.
- *Research performance*: A holistic approach is needed to make the best of Industry 4.0 technologies, facilitating the process of HCD in which both human and non-human actors are integrated towards human diversity, ergonomics, economics, manufacturability, and sustainability.
- *Research framework*: A new validated framework of HCD should take the points above into account and incorporate a well-rounded evaluation methodology to quantify the outcome of design activities across the life-cycle design phases. Besides, an interesting consideration in future research is to unify the relationships among the variants of HCD in order to embed them into the complete infrastructure of Industry 4.0.

These research schemes are challenging in a way that requires the increasing involvement of transdisciplinary collaboration in which researchers and industrial experts are brought together. This collaborative research is especially called in the phenomenon in which a transdisciplinary and multidimensional approach is required for a specific scientific topic (Chen & Duh, 2019; Hammer et al., 2018). This is also an approach for our next contribution.

Conclusion

Active work on developing methods, exploring influencing factors, and proving the effectiveness and efficiency regarding HCD show the increasing awareness of human roles in Industry 4.0. However, numerous studies have been brought into existence, but then subsequently disconnected from other studies. As a consequence, the application of these studies in industry and research alike is not regularly adopted, and the array of studies is broad and expands in different directions without forming a coherent structure. This study is one of the unique attempts to bridge the gap between the literature characteristics and the lessons learnt derived from an expository of case studies of HCD in the context of Industry 4.0. In order to sufficiently cover the research topic and provide evidence with a minimal amount of subjectivity and bias, this research performs SLR in which a special unit of analysis is given to the case studies, delivering the contributions in three ways. First, the approach to HCD claims to be transdisciplinary and multidimensional, which is evidenced by the overall literature characteristics: increasing research interest across disciplines and industries in different levels of analysis—product, workstation, company, and society.

Secondly, the transdisciplinary and multidimensional approach is also reflected by the in-depth review of case studies: the emerging trend, the design methods and lessons learnt. The review of the 43 case studies unfolds the emerging research themes—HCD, PSS, UCD—that deal with the challenges of personalization, servitization, and sustainability in the context of Industry 4.0. This phenomenon also leaves research space for the other concepts—HRC, HioTL, HMI—in smart manufacturing in the form of empirical research. Besides, the in-depth review also captures the wide range of design methods that are categorized in the four generic groups—discovery, clean-up, engineering, experiment—to tackle different problems scattered across different life-cycle design phases. Furthermore, the implementation of these design methods is also facilitated with the support of digital technologies: virtual and mixed reality, eye-tracking systems, digital modelling and simulation for virtual workplaces, IoT solutions, artificial intelligent. The variety in both quantitative and qualitative design methods associated with the supporting technologies expresses the necessity of the transdisciplinary and multidimensional approach for comprehending the methods in their proper context of use towards human diversity, ergonomics, economics, manufacturability, and sustainability. Therefore, for better adaption to the challenges, it is worth having cross-disciplinary collaborative research and/or improving the transdisciplinary skill sets of researchers and practitioners. This fact is further emphasized by the lessons learnt that dig into what the literature has achieved. The "Appendix" (Table 11)—which functions as a useful reference for the design of case studies—expresses the most important facts about the 43 case studies, resulting in the lessons learnt. These lessons learnt encapsulate various research results associated with limitations that are captured and harmonized in homogeneous groups: six groups of research results and four groups of research limitations. The research results are categorized into six groups: exploration of design success factors, achievement of engineering objectives, provision of supporting design frameworks, validation of the effect of human diversity on design, provision of transdisciplinary frameworks, and visualization of design scenarios. Different studies concentrate partially on their own expected results, which highlights a useful reference for future research that expresses both the transdisciplinary and multidimensional approach towards human diversity, ergonomics, economics, manufacturability, and sustainability in a comprehensive way. Besides, it is worth acknowledging the limitations—limited statistical power in result validation, lack of generalizability of research findings, further requirements of the supporting methods, lack of validation of the effectiveness—to enhance the robustness of the research findings. This will inspire research applications to both industry and research.

Third, the opportunities for future research regarding HCD in the context of Industry 4.0 are also provided to advance the research contributions in the coming years through the adoption of the lessons learnt from the previous works. Despite the rigor, relevance and expanse of this study, there are acknowledged limitations. Primarily, we applied the strict protocol of SLR with which some relevant papers might be overlooked. To minimize this, we searched eight databases to ensure a sufficient number of papers relevant to this topic to compensate for the missed papers—missed due to less relevance—by supplementing more relevant papers. Furthermore, we limited the papers to only peer-reviewed journal articles as a means to guarantee the quality of the publications. We also acknowledge that the selection of the topic, definition of search terms, and interpretation of the results are inseparable from our previous knowledge on the topic. Lastly, we assume that considerable knowledge resides among practitioners' experience and the grey literature.

The particular interest in this topic is the question of how to take advantage of literature, overcome its own acknowledged limitations, and advance research contributions in the body of knowledge. The first two questions are provided in this study, and the last one can be achieved by collaborative research in which transdisciplinary and cross-sectorial research centres and industrial partners join forces to contribute to a comprehensive common understanding of HCD in the transdisciplinary and multidimensional approach towards human diversity, ergonomics, economics, manufacturability and sustainability. This is also the approach for our next contribution to the field of HCD.

Appendix

See Tables 9, 10 and 11.

Table 9 Description of research databases

No	Database Name	Discipline	Description
1	Web of Science	Sciences, social sciences, arts, and humanities	Provides subscription-based access to multiple databases that provide comprehensive citation data for many different academic disciplines. It is currently maintained by Clarivate Analytics
2	Scopus	Life sciences; social sciences; physical sciences; health sciences	Provides the citation database of peer-reviewed literature: scientific journals, books and conference proceedings. From Elsevier
3	ScienceDirect	Physical sciences and engineering, life sciences, health sciences, social sciences and humanities	Provides subscription-based access to a large database of scientific and medical research. From Elsevier and related publishers
4	Emerald Publishing Limited	Management, business, education, library studies, health care, and engineering	Provides academic journals, books, and book series. Formerly MCB UP Ltd, the publisher changed its name to Emerald in 2002
5	SpringerLink	Science, technology, medicine, business, transport and architecture	Offers electronic and printed literature in different products: journals, books, series, protocols, reference works, and proceedings. From Springer plus journals from the publisher Wolters Kluwer
6	Engineering Village	Engineering	Provides integrated access to specialist databases as an information portal for engineering, applied science and technology. It includes Compendex and the Patents Office of the United States database
7	SAGE	Social sciences & humanities; health, life & biomedical sciences; engineering and physical sciences	Provides an independent, academic and professional publisher of different products, ranging from books, journals, online courses, etc.… SAGE has been part of the global academic community since 1965
8	EBSCO	Physics, electrical and electronics engineering, computers and control, information technology, manufacturing and production engineering	Provides comprehensive databases, ranging from general reference collections to specially designed and subject-specific databases for public, academic, medical, corporate and school libraries

Table 10 Adopted search syntax for each database

No.	Database name	Date	Search syntax *[**Search: by title, abstract, and keywords]*
1	Web of Science	21, June 2020	(TS = (("human centered design" OR "human centred design" OR "user centered design" OR "user centred design" OR "user experience design" OR "user oriented design" OR "human oriented design" OR "experience design" OR "service design" OR "interaction design") AND ("Industry 4.0" OR "industrie 4.0" OR "Cyber physical system*" OR "Cyber physical production system*" OR "smart manufacturing" OR "future manufacturing" OR "digital manufacturing" OR "smart factory" OR "future factory" OR "digital factory"))) AND LANGUAGE: (English) AND DOCUMENT TYPES: (Article)
2	Scopus	21, June 2020	TITLE-ABS-KEY (("human centered design" OR "human centred design" OR "user centered design" OR "user centred design" OR "user experience design" OR "user oriented design" OR "human oriented design" OR "experience design" OR "service design" OR "interaction design") AND ("Industry 4.0" OR "industrie 4.0" OR "Cyber physical system*" OR "Cyber physical production system*" OR "smart manufacturing" OR "future manufacturing" OR "digital manufacturing" OR "smart factory" OR "future factory" OR "digital factory")) AND (LIMIT-TO (DOCTYPE, "ar")) AND (LIMIT-TO (LANGUAGE, "English"))
3	Science Direct	06, June 2020	3.1. ("human centered design" OR "human centred design" OR "user centered design" OR "user centred design") AND ("Industry 4.0" OR "industrie 4.0" OR "Cyber physical system" OR "Cyber physical production system") 3.2. ("human centered design" OR "human centred design" OR "user centered design" OR "user centred design") AND ("smart manufacturing" OR "future manufacturing" OR "digital manufacturing") 3.3. ("human centered design" OR "human centred design" OR "user centered design" OR "user centred design") AND ("smart factory" OR "future factory" OR "digital factory") 3.4. ("user experience design" OR "user oriented design" OR "human oriented design" OR "experience design" OR "service design" OR "interaction design") AND ("Industry 4.0" OR "industrie 4.0" OR "Cyber physical system") 3.5. ("user experience design" OR "user oriented design" OR "human oriented design" OR "experience design" OR "service design" OR "interaction design") AND ("Cyber physical production system") 3.6. ("user experience design" OR "user oriented design" OR "human oriented design" OR "experience design" OR "service design" OR "interaction design") AND ("smart manufacturing" OR "future manufacturing" OR "digital manufacturing") 3.7. ("user experience design" OR "user oriented design" OR "human oriented design" OR "experience design" OR "service design" OR "interaction design") AND ("smart factory" OR "future factory" OR "digital factory")
4	Emerald	06, June 2020	(content-type:article) AND ("human centered design" OR "human centred design" OR "user centered design" OR "user centred design" OR "user experience design" OR "user oriented design" OR "human oriented design" OR "experience design" OR "service design" OR "interaction design") AND ("Industry 4.0" OR "industrie 4.0" OR "Cyber physical system*" OR "Cyber physical production system*" OR "smart manufacturing" OR "future manufacturing" OR "digital manufacturing" OR "smart factory" OR "future factory" OR "digital factory")
5	Springer Link	21, June 2020	("human centered design" OR "human centred design" OR "user centered design" OR "user centred design" OR "user experience design" OR "user oriented design" OR "human oriented design" OR "experience design" OR "service design" OR "interaction design") AND ("Industry 4.0" OR "industrie 4.0" OR "Cyber physical system*" OR "Cyber physical production system*" OR "smart manufacturing" OR "future manufacturing" OR "digital manufacturing" OR "smart factory" OR "future factory" OR "digital factory")
6	Engineering Village	21, June 2020	((((("human centered design" OR "human centred design" OR "user centered design" OR "user centred design" OR "user experience design" OR "user oriented design" OR "human oriented design" OR "experience design" OR "service design" OR "interaction design") AND ("Industry 4.0" OR "industrie 4.0" OR "Cyber physical system*" OR "Cyber physical production system*" OR "smart manufacturing" OR "future manufacturing" OR "digital manufacturing" OR "smart factory" OR "future factory" OR "digital factory")) WN KY)) AND (({ja} WN DT) AND ({english} WN LA)))

Table 10 (continued)

No.	Database name	Date	Search syntax *[**Search: by title, abstract, and keywords]*
7	SEGA Journals	10, June 2020	for [[All "human centered design"] OR [All "human centred design"] OR [All "user centered design"] OR [All "user centred design"] OR [All "user experience design"] OR [All "user oriented design"] OR [All "human oriented design"] OR [All "experience design"] OR [All "service design"] OR [All "interaction design"]] AND [[All "industry 4.0"] OR [All "industrie 4.0"] OR [All "cyber physical system"] OR [All "cyber physical production system"] OR [All "smart manufacturing"] OR [All "future manufacturing"] OR [All "digital manufacturing"] OR [All "smart factory"] OR [All "future factory"] OR [All "digital factory"]] Within Research Article
8	EBSCO	13, June 2020	("human centered design" OR "human centred design" OR "user centered design" OR "user centred design" OR "user experience design" OR "user oriented design" OR "human oriented design" OR "experience design" OR "service design" OR "interaction design") AND ("Industry 4.0" OR "industrie 4.0" OR "Cyber physical system*" OR "Cyber physical production system*" OR "smart manufacturing" OR "future manufacturing" OR "digital manufacturing" OR "smart factory" OR "future factory" OR "digital factory") Limited to: English, Peer-Reviewed, Academic Journals

Table 11 Summary of case study results according to literature

References	Design concepts	Context of case study	Objective	Design method	Evaluation methods	Research results[a] (RR)	Result limitations[a] (RL)
Schulze et al. (2005)	Human-centred design	Design for the computer-aided technology systems with respect to the production planning process at Daimler Chrysler AG	Identify requirements and success factors of a human-centred and computer-aided planning tool application	Iterative design *(participatory design, prototyping)*	Questionnaires *(8 planers for usability)* Interviews Scenario observation *(3 participants in a click-test scenario)*	(1) Large and time-consuming software projects for complex domains can be successful in applying human factors (2) Interdisciplinary and participative development of complex engineering applications are vital	(1) Limited information on determination of the required sample size (power) (2) Lack of generalizability
Lee and Abuali (2011)	Product-service systems	Design for value propositions at a company that specializes in the pressure-sensitive technology and self-adhesive solutions for consumer products	Demonstrate the pathway to the development of dominant design through effectively utilizing the proposed key tools	Quality function deployment *(combined with application mapping, novel innovation matrix)*	Undefined	(6) Provide the systematic thinking and dominant design of product–service systems that reply on the integration of novel tools	(2) It is unclear the findings are transferable to real environments (3) Lack of validation on the model´s effectiveness (4) In need of automation of the proposed tools
X. Wu et al. (2013)	Human-centred design	Design for a multi-function bike—a scooter and a tricycle—that can be used for both gliding and riding that fit the body size of children (aged 5–12)	Validate innovative product design using a rational multi-function method through functional superposition, transformation, and technical implementation	Human factors and ergonomics	Undefined	(1) The design innovates the design of children's bikes and extends the service life, which introduces energy saving features and develops intensive concepts	(2) Unreal industrial implementation (3) Lack of validation on the model's effectiveness
Zhu et al. (2015)	Product-service systems	Design for the knowledge-based support system in service operations of an aircraft engine	Focus on developing a knowledge-based support system for PSS design, and generating the PSS solutions to customer requirements	Quality function deployment Mathematical models *(analytical network process)* Iterative design *(prototyping)*	Undefined	(2) Customer requirements are considered during the design phase Knowledge could be identified and reused easily during PSS activities	(3) Lack of validation on the model´s effectiveness (4) In need of software development of the proposed tools

Table 11 (continued)

References	Design concepts	Context of case study	Objective	Design method	Evaluation methods	Research results[a] (RR)	Result limitations[a] (RL)
D. Chen et al. (2016)	Human-centred design	Design for pan-ethnic-group products with collection of various types of pictures that are assessed by emotional semantic feedbacks from user perspectives	Validate the proposed method of pan-ethnic-group products based on the gene clustering method and emotional semantic analysis	Mathematical models *(fuzzy set theory, principal component analysis)*	Undefined	(1) Improve the agility of the product design process in Industry 4.0 (2) User percepts are considered at an early stage of product design	(2) Unreal industrial implementation (3) Lack of validation on the model´s effectiveness
L. Wu et al. (2016)	Human–machine interface	An experimental study on an eye tracking in LED manufacturing systems to measure three levels of interface complexity on user experience	Investigate the relationship between user experience and interface design with respects to the complexity levels and user background	Human factors and ergonomics	Questionnaires *(subjective participants' responses with 19 experts and 19 novices)* Statistics *(hypothesis testing)*	(3) User experience is significantly affected by the factors, including the interface complexity and user background	(1) There is limited information on the determination of required sample size and the participants are all from the same company. Therefore, this study has a potential bias
R. Y. Chen (2016)	User-centred design	Design for complex interactions and experiential design system with fuzzy dual experience-based design on consumer electronic products	Illustrate the usability of the proposed model and its sensitivity analysis	Mathematical models *(fuzzy decision tree, fuzzy cognitive map, analytic hierarchy process)*	Mathematical models *(linear programming)*	(1) Find the optimal profit of the design quality in relationship between market price and experience's product value (2) Both the engineer's experience and customer's experience are important	(2) It is unclear the findings are transferable to real environments (4) The quality of the model will depend on the input case data as well as computational capability
Song et al. (2016)	Human–machine interface	A user study using a paper prototype (wireless connections) to investigate how information of interface design are interpreted and evaluated by users	Assess whether the revised interface, with the proposed method, helps users accomplish their tasks	Iterative design *(research through design)*	Scenario observation *(10 non-expert users, and 5 participants for the printer-iPad connection)*	(6) Provide a design framework for interpreting and resolving complex user interactions	(1) Limited statistical power (2) Lack of generalizability of results to all applications

Table 11 (continued)

References	Design concepts	Context of case study	Objective	Design method	Evaluation methods	Research results^{a} (RR)	Result limitations^{a} (RL)
Jung et al. (2017)	User-centred design	Design for mitigation of the elderly's growing fatal accidents by considering concept usability and body conditions in the different countries: South Korea, United States of America, and the United Kingdom	Understand what kinds of driving problems elderly drivers have and demonstrate how new system concepts could be developed	Iterative design *(interviews, questions, focus groups, observation)*	Questionnaires Interviews *(60 elderly people)*	(3) Provide different perspectives to anticipate safe and usable solutions of elderly drivers in hopes of mitigating accidents	(1) Limited statistical power (2) Lack of generalizability of results to all other regions
Kymäläinen et al. (2017)	User-centred design	Design for new interaction methods and ambient intelligence of an oil refinery factory focusing on the production of advanced and low-emission traffic fuels in Finland	Demonstrate the future-oriented user experience research through the method of video-illustration	Iterative design *(science fiction prototyping)*	Questionnaires Interviews *(23 operators)*	(4) Show the reflection of creation process and how the experience-driven with video-illustrated prototype is evaluated	(1) Encompass degrees of subjectivity and rely on knowledge, judgment and projection (2) Lack of generalizability of results to all applications
Leng and Jiang (2017)	Product-service systems	Design for a reference model of the historical service cases from a manufacturing context of a special printing machinery enterprise group in a China Technology Zone	Aim at illustrating the practicality of the proposed approach for new product and service development	Mathematical models *(fuzzy set theory and quotient space)*	Mathematical models *(Fuzzy tolerance quotient spaces)*	(2) The proposed approach is suited to be applied on real-world data to extract and reuse the "best practice" knowledge from historical cases	(4) The quality of the model will depend on the input case data as well as computational capability
Ma et al. (2017)	User- centred design	Design for customer requirements translated into product specifications in the context of high-speed train	Verify the rationality and feasibility of the multidisciplinary requirement modelling	Iterative design *(interviews)* Quality function deployment	Undefined	(5) Guide the multidisciplinary collaborative design that can be inversely mapped into each disciplinary	(3) Lack of validation on the model´s effectiveness (4) 'Manual' application of the proposed methodology

Table 11 (continued)

References	Design concepts	Context of case study	Objective	Design method	Evaluation methods	Research results[a] (RR)	Result limitations[a] (RL)
Pacaux-Lemoine et al. (2017)	Human- centred design	Design for human integration in intelligent manufacturing systems in which two technongy-centred approaches—without and partial human involvement—are compared with HCD	Validate the proposed framework of HCD on production demonstrator Focus on the issue of human-system cooperation	Human factors and ergonomics	Questionnaires *(1 survey for the workload and acceptability evaluation)* Performance comparison	(1) Improve the global production objectives Facilitate human operator workload	(1) Limited statistical power (2) Unreal industrial implementation
Boy (2018)	Human- centred design	Design for human-systems integration in which the Mars 500 experiment was carried out	Understand the long-term isolation in a limited room space with different cultural crews of volunteers	Iterative design *(participatory design)*	Undefined	(3) Three major issues are elicited: time effects; cultural influences; and individual differences	(3) Lack of validation on the model´s effectiveness
Kaasinen et al. (2018)	Human- centred design	Design for a comprehensive coverage of maintenance work in the context of Industry 4.0 with four industrial demonstrators	Illustrate how industrial maintenance work could benefit from knowledge-sharing solutions based on Industry 4.0	Iterative design *(field studies, interviews, observation)*	Questionnaires *(2 maintenance technicians)* Scenario observation Interview	(4) Illustrate the user experience of future maintenance work that shares knowledge with peers and make reports effortless	(1) Limited statistical power (2) Problematic design and technology applications related to wearable devices
Lin (2018)	User- centred design	Design for a user experience-based design approach with a glass recycling company in Taiwan to enhance recycling incentives and empower Industry 4.0	Verify the proposed approach's practical feasibility	Iterative design (*UNISON framework of data-driven innovation, questionnaires*)	Undefined	(2) Understanding users' preferences and actual needs is critical (6) Enable follow-up experiments for reference and modification to facilitate understanding of changing user preferences	(3) Lack of validation on the model´s effectiveness (4) Focus only short-term user data that are required to be updated every season for new insights

Table 11 (continued)

References	Design concepts	Context of case study	Objective	Design method	Evaluation methods	Research results[a] (RR)	Result limitations[a] (RL)
Mazali (2018)	User-centred design	A study on the links among digital society, digital culture and Industry 4.0 in the context of an Italian plant where high-speed trains are produced	Examine the change that workers are subject to and along with the work organization in smart digital factories	Iterative design *(interviews)*	In-depth interviews *(40 interviews were conducted with managers and middle managers)*	(2) User-mental models and sense-making need to be updated with social and organizational contexts that involve stakeholders and new roles of intelligent systems in workflows	(1) Limited statistical power (2) The extension to additional companies and sectors is required to achieve a generalization
Mostafazadeh Davani et al. (2018)	Human–machine interface	Design for a 3D based meta user interface that is specifically developed to support interaction with ambient intelligence systems	Illustrate the designed meta-UI that can increase usability of the human-meta system interaction	Iterative design *(focus groups, GUI prototyping, cognitive walkthrough)*	Questionnaires *(6 participants with the System Usability Scale questionnaires)*	(6) The proposed meta-UI can support the usability of human-meta system interaction	(1) Limited statistical power (2) Lack of generalizability of results to all applications
Mourtzis et al. (2018)	Product-service systems	Design for the quantification of PSS customization complexity in the context of machining industry that is exemplified with 30 product-service alternatives	Aim at evaluating the different alternatives of PSS in terms of complexity	Mathematical models *(geometric vectors, linear algebra)*	Mathematical models *(Vector Analysis in the Euclidian space)*	(2) The competitiveness and sustainability of enterprises can be maintained by monitoring their PSS throughout their life cycle (6) Estimate the complexity of different design alternatives towards the selection of PSS	(2) The model does not address other factors, such as need/nature of different industrial companies (4) Require development of a software application for computation
Pezzotta et al. (2018)	Product-service systems	Design for PSS along their entire life cycle in the industrial context of a mould-making B2B Greek small-medium size enterprise	Develop and validate the proposed methodology of Product Service System Lean Design Methodology	Iterative design *(traditional brainstorming, focus groups, cognitive walkthrough and Wizard of Oz, prototyping)*	Face-to-face workshop	(6) Create PSS that are customer driven, economically sustainable in the long term and avoid valueless reworks and activities	(2) It is unclear the findings are transferable to real environments

Table 11 (continued)

References	Design concepts	Context of case study	Objective	Design method	Evaluation methods	Research results[a] (RR)	Result limitations[a] (RL)
Richert et al. (2018)	Human–robot collaboration	Design for the hybrid human–machine team (socializing with robots) by using Cinema 4D and Unreal Engine in which participants are randomly assigned to four different set-up conditions	Analyse hybrid cooperation and team building in a controlled setting in which a production hall and a robotic teammate are built	Human factors and ergonomics	Questionnaires *(112 out of 153 student responses)* Statistics *(hypothesis testing)*	(2) The hybrid team humanoid appearance might be a more stable condition for different personality types and vice versa for the case of machine-like robots	(1) Limited statistical power and the participants are not intended end-users (2) It is unclear the findings are transferable to real environments
Wang et al. (2018)	Human-centred design	Design for smart clothing prototypes embedded with micro-sensors and light-emitting diodes (LEDs) functions to enhance human emotional expression	Validate a methodology bridging the gap between human emotions and wearable technologies for interactive fashion innovation	Iterative design *(prototyping)* Kansei engineering	Questionnaire *(emotional survey)* Scenario observation *(34 participants with Kansei method)*	(2) The functionality should synchronize with the requirements of human emotional expression to stimulate the emotional response	(1) The participants' wearing experience time is limited, and the evaluation is mainly subjective
Anke (2019)	Product-service systems	Design for a meta-model and web-based tool to combine the financial assessment with service design that embraces collaborative teamwork	Evaluate the tool in which multiple teams carry out the design and evaluation of smart services	Iterative design *(a web-based tool prototype)*	Questionnaires *(30 participants)*	(5) Provide inter-disciplinary teams a tool-based structuring support for the design and evaluation of smart services	(1) Limited statistical power (4) Further clarification of conditions under which the usage of the tool becomes more effective is required
Caputo et al. (2019)	Human- centred design	Design for ergonomics to preventively solve ergonomic risks by simulation with a 'Fiat Panda' assembly line	Validate an appraisal of workplace design towards preventive ergonomics by virtual workplace simulation	Human factors and ergonomics	Mathematical models (Simulation *with data from assembly tasks simulation of Digital Human Models)*	(1) It is possible to preventively solve ergonomic risks during the design phase	(2) Unreal industrial implementation
Ceccacci et al. (2019)	Human- centred design	Design for ergonomics to understand the relationship among ergonomics, safety and risk classification in the context of manual assembly of the Cooker Hood Line	Demonstrate the proposed multi-path methodology to support the application of ergonomic risk management in practice	Human factors and ergonomics	Ergonomic analysis Physical ergonomic assessment (RULA) *(2 participants)* Interviews *(8 participants)*	(1) Provide the definition of crucial risk factors and selection of proper ergonomics assessment associated with measurement tools	(1) Limited statistical power (2) Without taking into account psychosocial stressors (4) Manual application of the proposed methodology

Table 11 (continued)

References	Design concepts	Context of case study	Objective	Design method	Evaluation methods	Research results[a] (RR)	Result limitations[a] (RL)
Fu et al. (2019)	Human- centred design	Design for a model of cyber-physical public design to explore the three dimensions: residents' information exchange, friends' interaction and personal emotion	Illustrate the model of data collection on residents' lives, improve and rebuild the urban communities to meet the needs of the public	Iterative design *(participatory design)*	Questionnaire *(8 participants* via *living lab experiment)* Scenario observation	(2) User data can improve the interaction experience sustainably Integrating virtual and real world plays an important role in the construction of smart cities	(1) Limited statistical power (2) Unreal industrial implementation
Grieger and Ludwig (2019)	Product-service systems	Design for digital service in providing parking spots of a major Swedish spare-part supplier	Evaluate the proposed conceptual reference framework of digital service conceptualization in the early design phase	Iterative design *(five guideline-supported interviews)*	Interviews *(3 OEM employees and 1 IT external industry expert)* A case study workshop	(2) Support the early development stage by giving a structure and a customer-centric direction	(1) Limited statistical power (4) A set of supplementary tools for service development is required
Haber and Fargnoli (2019)	Product-service systems	Design for the product and service integration to achieve functional results with offering's value at a manufacturer that produces hemodialysis devices associated with services	Validate the proposed model' application	Iterative design *(questionnaires, interviews)* Quality function deployment Mathematical models *(Thurstone's Law of Comparative Judgments)* Kano model	Undefined	(6) Facilitate the company to collect information in the case of incomplete answers to surveys and questionnaires, which provides a practical method to handle the uncertainty	(2) The "end" users of the equipment (i.e. the patients) is not considered (3) Lack of information in effectiveness validation on the proposed solutions
Harwood et al. (2019)	Product-service systems	Design for a diegetic prototyping methodology to investigate service innovations that reflect future uses of new and emerging technologies	Provide an example of IoT applications, illustrate the central proposed tenets, and identify key issues	Iterative design *(science fiction prototyping)*	Questionnaires *(1,200 respondents)*	(4) Facilitate visualization that examines future possibilities of service innovations-in-use by overcoming abstract verbal descriptions of new technologies	(1) Limited statistical power with certain degrees of subjectivity, judgment and projection
Hoe (2019)	Human- centred design	A study on the digitalization journey in the context of community hospital and social service agency that deliver holistic care for seniors	Illustrate the relevant five disciplines in the digitalization journey: personal mastery, mental models, shared vision, team learning and system thinking	Empirical experiments	Undefined	(2) The patient centric model is a key of success (3) Alleviate the issue of overcrowding in hospitals, medication non-compliance and social isolation of seniors	(3) Lack of information in effectiveness validation on the proposed solutions

Table 11 (continued)

References	Design concepts	Context of case study	Objective	Design method	Evaluation methods	Research results^a (RR)	Result limitations^a (RL)
Kong et al. (2019)	Human-in/on-the-loop	A study on design consideration for industrial wearable systems addressed by three world-leading development groups	Review and analyse academic progresses to provide insights into the past, present and future of industrial wearable systems	Iterative design *(questionnaires)*	Questionnaires Interviews Workshops *(25 company representatives)*	(5) Structure a new framework with three aspects: design scalability, reconfigurability and robust architecture	(1) The propositions require testing by further quantitative methods
Peruzzini et al. (2019)	Human- centred design	Design for assembly stations in collaboration with CNH Industrial to validate the use of the multimodal approach in workplace and product design (tractors' cabin)	Validate the proposal with the application of VR technologies that allow for interactive design of products towards HCD	Iterative design *(Norman's interaction design model)* Human factors and ergonomics	Questionnaires *(4 novices and 4 experts)* Scenario observation	(2) Have a precise and objectified feedback about interaction design before the product/process realization to improve the system design or re-design	(1) Limited statistical power (4) Costs and Complexity of the set-up, and the need of multiple data collection and synchronization
Prinz et al. (2019)	Human-in/on-the-loop	Design for a graphical I4.0-enabled engineering method that is prototyped and implemented in three manufacturing scenarios: automated station, manual workplace, transport system	Evaluate the proposed method with case studies in which participants are asked to solve multiple engineering tasks	Iterative design *(prototyping)* Business Process Modelling and Notation	Questionnaires *(10 participants)* Performance comparison Statistics *(hypothesis testing)*	(1) Significantly outperform the conventional method in terms of required engineering times and subjective ratings	(1) Limited information on determination of the required sample size (power)
Turetken et al. (2019)	Product-service systems	Design for an integral component of a business engineering framework that introduces the service-dominant business model radar in the mobility domain	Evaluate the proposed model for its validity and utility	Iterative design (*focus groups)*	Workshops (15 *workshops with 161 practitioners designing blueprints for 21 new business models)* Questionnaires *(36% response rate)*	(2) Take advantage of various capabilities of multiple parties to offer value to customers (5) Develop a business modelling that motivates a collaborative approach	(1) Limited statistical power (2) It is unclear the findings are transferable to real environments

Table 11 (continued)

References	Design concepts	Context of case study	Objective	Design method	Evaluation methods	Research results[a] (RR)	Result limitations[a] (RL)
Vanderhaegen (2019)	Human-in/on-the-loop	Design for human–machine systems on the rail flow control with the experiments: automation-supported human and human-supported automation	Test the proposed concept with two case studies on rail flow control in relation to pedagogical learning supports	Empirical experiments	Questionnaires *(56 students)* Scenario observation	(2) Adapt the online learning process to individual requirements and limits	(1) Limited statistical power
Witschel et al. (2019)	Product-service systems	A case study on the mechanism behind digital capabilities toward digitization in large German companies	Explore causal mechanisms and the derivation, test and develop theoretical constructs	Iterative design *(interviews, theory-guided approach for text analysis)*	Interviews *(15 semi-structured interviews with executive and senior managers from 8 larger companies)*	(2) Digital capabilities are only effective, if there is an alignment between strategy, organizational and leadership mindset	(2) Lack of generalizability of results to all types of industries and firms
Wojtynek et al. (2019)	Human–robot collaboration	Design for a collaborative robot combined with Plug-and-Produce system where participants perform a flexible work-cell setup	Evaluate both the technical aspects: the usability of the smart system, and human factors	Human factors and ergonomics Empirical experiments	Questionnaires *(17 participants university spectrum and laboratory co-workers)*	(1) Participants do not excessively extend physically and mentally during the experimental scenarios	(1) Limited statistical power
Adrodegari and Saccani (2020)	Product-service systems	A study on a servitization maturity model that aims at assessing and positioning companies in the context of a medium machine-tool builder and a forklift truck firm	Exemplify how the proposed model supports companies in identifying and bridging the gaps in order to deploy a servitized model	Iterative design *(a full-day meeting with the top managers)*	Interviews	(6) Support SMEs in the servitization journey, and help them bridge the distance with large companies	(2) The extension to additional companies and sectors is required to achieve a generalization
Grandi et al. (2020)	Human- centred design	Design for serviceability with mixed reality to evaluate two different use cases that support human-centred system development in tractor design	Demonstrate a way in which the proposed approach can support human-centred system development	Human factors and ergonomics	Questionnaires *(1 user)* Performance comparison *(on ergonomic aspects with the support of MR tools)*	(2) Digital technologies can provide both the physical and digital worlds that allow to foresee interactions to predict and fix design criticalities	(1) Limited statistical power

Table 11 (continued)

References	Design concepts	Context of case study	Objective	Design method	Evaluation methods	Research results[a] (RR)	Result limitations[a] (RL)
Gualtieri et al. (2020)	Human- centred design	Design for a robotic collaborative workstation of a wire assembly line that interacts with an operator in an ergonomic and efficient way	Demonstrate improvements in the ergonomics in terms of productivity and reduction of biomechanical overload	Human factors and ergonomics	Ergonomic analysis Physical ergonomic assessment (RULA) *(2 participants)*	(1) Perform an accurate assessment of ergonomics in the early design phase Improve productivity and reduce biomechanical overload	(1) Limited statistical power (2) Further improvement is required to replace the RULA method that is more suitable for preliminary postural assessment
Van Acker et al. (2020)	User-centred design	A study on the understanding of employee objections to wearing gauges of wearable mental workload as leveraged by Industry 4.0	Test a hypothesis of how user acceptability of technology depends on the technology's goals and implementation context of the wearing gauges	Iterative design *(questionnaires)*	Questionnaires *(150 participants for pilot study and 350 responses for pre-registered study with gender analysis)* Interviews Statistics	(3) Technology readiness, gender, education, and possibly proper privacy management are found to play a crucial role	(1) Limited information on determination of the required sample size (2) The replication of research result was not successful
van Lopik et al. (2020)	User-centred design	Design for knowledge sharing between expert and novice workers during the phone repair task with an augmented repair training application	Implement and evaluate the proposed application	Iterative design *(iterative refinement through usability testing and feedback)* Human factors and ergonomics Empirical experiments	Questionnaires *(5 participants)*	(2) Engage management is highly recommended (6) Help small enterprises explore the value of AR whilst causing minimal disruption and limited financial investment	(1) Limited statistical power (4) The need for data protection, maintenance and storage were not directly addressed
Zhang et al. (2020)	Product-service systems	Design for an environmental model-driven interaction of smart products through-life design of service and maintenance, which is virtual and supported by integrated software solutions	Evaluate the model´s implementation feasibility in an industrial case study of smart high-speed train	Iterative design *(Norman's interaction design model)*	Undefined	(2) Address intelligent interactions with external environments and relevant stakeholders (6) Map out the interaction requirements between the smart product and other interaction elements	(3) Lack of information in effectiveness validation on the proposed solutions (4) Required ability to achieve the computerization of the design framework

[a] The extracted items are numbered and categorised in the same corresponding numbered groups (RR1, RR2, RR3, RR4, RR5, RR6, RL1, RL2,RL3, RL4) in accordance with their affinity

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CHAPTER 4

Datasets of skills-rating questionnaires for advanced service design through expert knowledge elicitation

Brief summary

To effectively develop advanced services, one of the key design elements is to provide design team members (also known as design practitioners) with appropriate design skills, such as market research or prototyping skills. This is crucial because design skills have a significant impact on the key performance indicators of design work (Baines & W. Lightfoot, 2013; Karpen et al., 2017), and they enable designers to comprehend their short-term functions and long-term professional development, which enhances a company's sustainable growth (Spreitzer et al., 2012).

Nevertheless, there is a scarcity of research studies that pinpoint the specific design skills that are necessary for design teams (Richter et al., 2019). This aligns with our review work (Chapter 3), where none of the analyzed case studies delved into design skills in detail. Design skills, in this context, refer to the ability of a design practitioner who employs specific new service development methods to perform design tasks (e.g., market research or agile prototyping).

To advance the research in this area, the current study addressed a gap by answering the following research question: Who (design team members regarded as internal stakeholders, e.g., an engineer, a financial analyst, a marketer) needs to know and/or practice what design methods (e.g., interview techniques, prototyping) as design skills, to perform one or more design activities (e.g., to understand the customer’s latent needs, or to use wireframes for prototyping)?

Answering this primary research question will assist design practitioners in establishing internal service capability by identifying who needs to be trained in what and deciding on training priorities based on their business resource constraints. Additionally, the study provides useful answers to secondary research questions: (1) Who should be trained in what design methods?; and (2) How can these design methods be prioritized in building service capability (training and skills enhancement)? The answers to these research questions may vary depending on the use context (e.g., company size, design knowledge, and experience) and the perspective of the respondent, leading to an unstructured decision problem.

To address the problem, experts who possess expertise in both academic and industrial perspectives are best suited to provide answers (R.R. Hoffman et al., 2008; Robert R. Hoffman et al., 1995). Therefore, the current study conducted an expert survey to collect data and obtain expert knowledge related to advanced service design to answer the research questions. Purposive sampling and a chain referral approach were utilized to recruit appropriate experts for the questionnaire-based research. Furthermore, to enhance research validity, the analytical hierarchy process (AHP) was applied to design pairwise skills-rating questionnaires that would elicit and validate expert responses to the research questions. The resulting dataset from expert responses was processed using AHP algorithms programmed in the R programming language. The present study also provides transparent data and available codes in the supplementary information.

The final analysis results are presented in Table 2 and summarized in Section 2.2, Chapter 2. Based on Table 2, for the primary research question, for instance, in the skill set of 'idea exploration,' designers and engineers/technicians should preferably have a better grasp of the skill set than other groups of design team members based on the aggregated perspectives ("S") of all surveyed experts for the primary research question. Based on Table 2, the same rationale applies to the remaining design team members and design method groups.

Similarly, the answers to the two secondary research questions – (i) who should be trained in what design methods, and (ii) how can these design methods be prioritized in building service capability – are also based on Table 2. As an example, in the skill set of 'participatory design', designers, marketing analysts, and engineers/technicians should receive training for the skill set in the same order of priority. As indicated in Table 2, the demand for the skill set of designers is the highest, except for the 'business analytics' skill set (such as game theory and profit formula), which should be primarily prioritized for executive officers and financial analysts.

Aside from designers, engineers should not only possess technical skills such as prototyping, operations-centered methods, and engineering methods, but they should also be trained in the skill sets of idea exploration and participatory design, which can help them understand both tangible and latent customer requirements. As a result, the dataset and its analysis results enable researchers and design practitioners to create a transdisciplinary design team in which each group of design methods can be managed by two or three job roles, in order of priority.

In conclusion, the present study has contributed to the field by identifying design skills (Table 2) regarded as one of the key design elements. At this stage, the key design elements identified from Chapter 3 (life-cycle service design, stakeholder networks, new service development methods) and this study (design skills)—address RQ1: What are the key design elements of an effective HCD methodology for advanced services? As a result, they are ready to be compiled to form a new multidimensional design methodology for advanced services (DIMAND). DIMAND is presented in Chapter 5 and addresses RQ2: How are the identified key design elements and their relations incorporated in a single-view structure in accordance with a human-centric approach?

Despite the rigorousness of this research, the present study acknowledges that there are limitations associated with pre-coded (closed) skills-rating questionnaires. These closed questionnaires in practice do not allow for other possible choices (design team members and design methods); this limitation of closed-ended questionnaires has also been acknowledged by other questionnaire-based research studies (Brigham, 1975; Z. Chen et al., 2022; Reeve-Brook et al., 2022). For instance, the expert or design practitioner may consider the role of the sales team in addition to the defined design team members (see Table 2) for advanced service designs.

The full content of the present study is presented below.

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DATA DESCRIPTOR

Datasets of skills-rating questionnaires for advanced service design through expert knowledge elicitation

Hien Ngoc Nguyen[1]✉, Ganix Lasa[1], Ion Iriarte[1], Ariane Atxa[1], Gorka Unamuno[2] & Gurutz Galfarsoro[3]

This article presents a dataset of service design skills which service design experts value as important requirements for design team members. Purposive sampling and a chain referral approach were used to recruit appropriate experts to conduct questionnaire-based research. Using the analytical hierarchy process (AHP), pairwise skills-rating questionnaires were designed to elicit the experts' responses. The resulting dataset was processed using AHP algorithms programmed in R programming language. The transparent data and available codes of the research may be reused by design practitioners and researchers for replication and further analysis. This paper offers a reproduceable research process and associated dataset for conducting multiple-criteria decision analysis with expert purposive sampling.

Background & Summary

Today, product-oriented companies are discovering new value creation methods that enable them to increase customer satisfaction, market share and competitiveness for improved economic returns and sustainability. New value creation can be achieved with new business models that help these companies to extend their services by means of their product-service systems (PSS), that is, systems representing bundles of products and services[1–3]. The existing literature often classifies these services according to three service groups: basic services (e.g., spare parts delivery and provision of tools and accessories), intermediate services (e.g., training, repair and maintenance), and advanced services[3–5]. In contrast to the first two classifications, advanced services offer new value creation by focusing on the delivery of product-service performance outcomes in terms of use-based and/or result-based contracts[4,6]. These contracts allow a customer to pay based on a result, output, performance and/or outcome of product-service delivery. Some typical cases of such contracts include the 'power-by-the-hour' model in terms of which Rolls-Royce receives a fixed price for each hour their engines work for customers[7], and the 'pay-per-lux' model where the customer buys a subscription from Philips for a certain amount of light per year instead of buying Philips' lamps[8].

In order to design these advanced services, one of the key design elements is to equip the design team members (design practitioners) – or internal stakeholders of a company that seeks advanced service designs – with proper design skills (e.g., skills in market research or prototyping)[9]. This is important because design skills affect the key performance indicators in design work[4,10] and help designers to understand their short-term functioning and long-term work development, enhancing the sustainable development of a company[11]. However, there are few research studies that identify which specific design skills are required by design teams[9,12]. To advance research in this area, a dataset was generated to answer the primary research question:

- *Who* (design team members, e.g., an engineer, a financial analyst, a marketer) needs to know and/or practice *what* design methods (e.g., interview techniques, prototyping) as design skills, to perform one or more design activities (e.g., to understand the customer's latent needs, or to use wireframes for prototyping)?

[1]Mondragon Unibertsitatea: Design Innovation Center (DBZ) - Faculty of Engineering Loramendi, 4, 20500, Arrasate - Mondragón, Gipuzkoa, Spain. [2]IDEKO, Arriaga kalea, 2, E-20870, Elgoibar, Gipuzkoa, Spain. [3]UROLA, Urola Kalea, s/n - Apdo 3, 20230, Legazpi, Gipuzkoa, Spain. ✉e-mail: nhneguyen@mondragon.edu

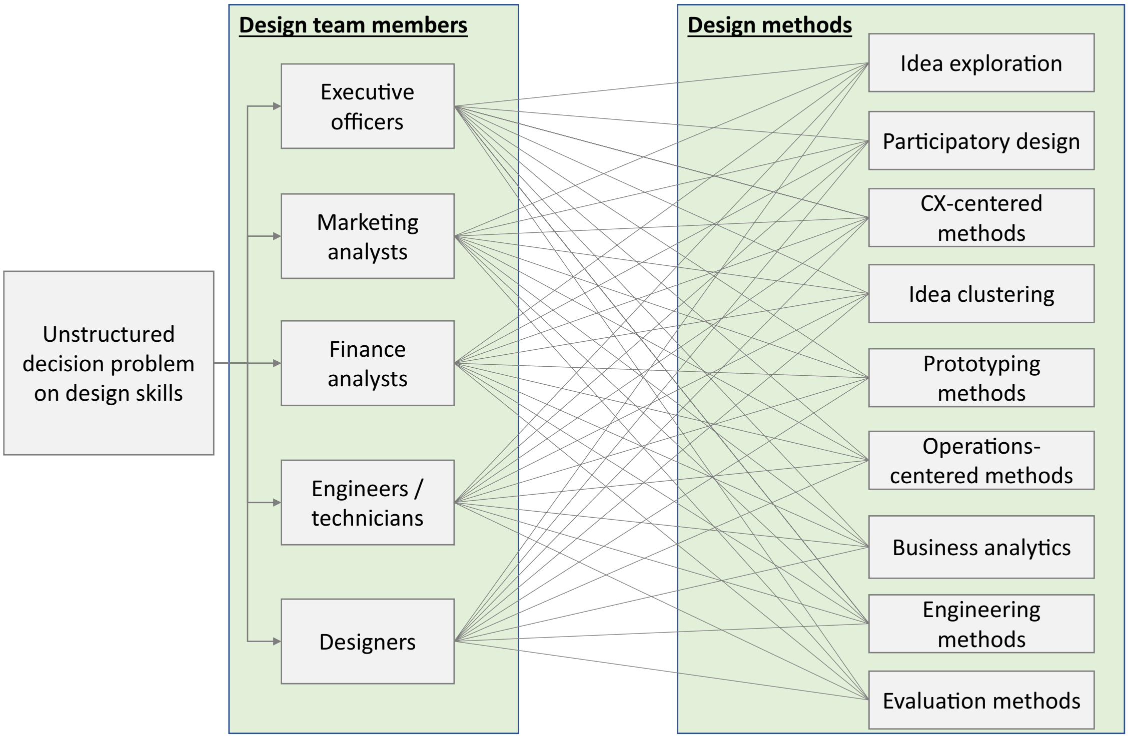

Fig. 1 Unstructured decision problem on design skills. The decision problem is who (design team members) needs to know and/or practice what design methods, as design skills, to perform one or more design activities (e.g., to understand customer latent needs, to use the wireframes for prototyping). For further description of these design methods, refer to the dataset[21] with the attached file name (.pdf): (Expert Survey) Skill-rating questionnaires.

The answer to this primary research question will also help design practitioners to build internal service capability ('who needs to be trained in what') and make decisions on training priorities in terms of their business resource constraints. Therefore, the captured dataset is also useful to answer the following two secondary research questions:

- *Who* should be trained in *what* design methods?
- *How* can these design methods be prioritized in building service capability (training and skills enhancement)?

The answers to the research questions can be varied, as they depend on the use context (e.g., company size, design knowledge and experience) and the perspective of the person answering the questions, leading to an unstructured decision problem. To tackle this problem, experts are in the best position to provide answers based on their expertise from both academic and industrial perspectives[13,14]. Therefore, the authors conducted an expert survey from which a dataset was developed to elicit expert knowledge related to the field of advanced service design in order to answer the research questions.

This dataset aims to enable design practitioners to determine which service design skills are valued for design teams from the perspective of service design experts, enabling practitioners to build internal service capability. Practitioners can use the dataset, methodology, data records and available R codes presented in the following sections to easily obtain expert knowledge for their own research contexts and practice. Researchers can also refer to this reproduceable research method for conducting multi-criteria decision analysis following expert purposive sampling.

Methods

Designing the expert survey. The questionnaire design for the expert survey was based on the primary research question. In previous studies, researchers conducted a systematic review of the literature in the field of human-centered design for advanced services[12] to define the two main elements of the primary research question: (1) who needs to know and/or practice (2) what design methods, as design skills, to perform one or more design activities. The systematic review resulted in: (1) five groups of design team members, and (2) nine groups of design methods, as summarized in Fig. 1. Figure 1 depicts an unstructured decision problem in which a design team member (e.g., an executive officer or a financial analyst) may employ one or more design methods (e.g., idea exploration or prototyping methods). The decisions can be varied, as they depend on the use context and the expertise of the person who makes the decision. As mentioned, the expertise of the service design experts was used to make these decisions as well as recommend to the design practitioners which decisions should be made.

To develop the right type of survey questionnaire, the authors applied the analytical hierarchy process (AHP) to design pre-coded (closed) pairwise questionnaires – based on a nine-point rating scale – for the expert survey.

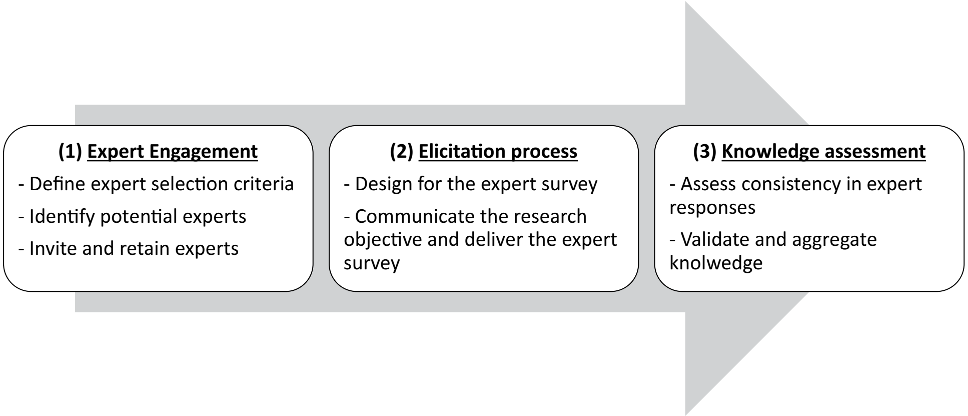

Fig. 2 The procedure for the expert purposive sampling.

In the literature, the AHP is used to interrogate people who have extensive knowledge about a specific topic[15,16]; this method is commonly used for a small sample size[17]. It may also help experts or decision-makers to set priorities and make the best decision in a wide variety of decision situations in diverse fields, for example, design concept evaluation[16], assessment of distribution center locations[18], determination of potential groundwater recharge zones[19], to name a few. The AHP has several functions, such as (i) breaking an unstructured problem down into rational hierarchical decision elements, and (ii) eliciting the best prioritized decisions from experts or decision-makers through questionnaires using pairwise comparisons of individual groups of elements. The answers to the survey provided by the experts can be varied, which would lead to inconsistency or subjective bias. This problem was avoided by validating the consistency of participants' responses using consistency ratios (CRs) computed by the AHP[20].

The authors broke down the primary research question by eliciting expert knowledge through pairwise skills-rating questionnaires, in accordance with the AHP. These skills-rating questionnaires of the expert survey are fully presented in the dataset[21] with the attached file name (.pdf): *(Expert Survey) Skill-rating questionnaires*.

Expert engagement.

To effectively elicit expert knowledge on the primary research question using skills-rating questionnaires, a proper selection from the spectrum of experts was required. Therefore, the authors followed a rigorous sampling method, which is embraced by scientists as one of the purposive sampling techniques[22,23]. This sampling method, even more so with a small sample size, incorporates a measure of uncertainty in respect of the elicited expert knowledge and should therefore include an assessment of the validity of the findings[24]. This validity can be achieved by following the sampling procedure illustrated in Fig. 2.

Figure 2 starts with the expert engagement, in which the selection criteria for experts should be clearly defined[24–27]: (1) expertise relevant to the research question, (2) diversity in expertise, (3) willingness and dedicated to the research inquiry. Another expectation is related to the sample size of the expert panel. The literature suggests that the number of participants will vary according to the scope of the problem and the resources available (e.g., time and money)[28,29]. However, there is very little actual empirical evidence regarding the effect of the number of participants on the reliability or validity of consensus processes[30]. Because expert panels do not need to be representative samples for statistical purposes, representativeness is assessed based on the qualities of the expert panel following the expert selection criteria rather than the number of experts[31]. In practice, an empirical expert panel should consist of a minimum of 10 participants[16,32].

Based on the expert selection criteria and the sampling guidance, the authors recruited 10 recognized experts, representing both industry and academia, from international workshops in the relevant fields; some of the experts were also selected using a chain referral approach in terms of which the initial experts nominated additional experts. These experts, whose profiles are presented in Table 1, have worked in various countries (the UK, France, Spain, Germany, and Japan), and represent diverse disciplines, such as human-centered design, related fields in Industry 4.0, servitization, business models and sustainable product-service systems. Therefore, the expert recruitment process ensured that their inputs were transdisciplinary.

Elicitation process and knowledge assessment.

After engaging the experts, the next step (see Fig. 2) was to send out the invitations and retain the experts via formal emails, which explained the topic of the research, namely design skills, and the research objectives. Next, the expert survey (the pdf file in the dataset[21]) was sent to the experts (see Table 1) via email in September 2021. All the expert responses were collected via returned emails around November 2021. The raw data (the expert responses) were inputted in the spreadsheet (the xlsx file in the dataset[21]). Lastly, the data were analyzed using the AHP with R codes (the html file in the dataset[21]), which resulted in the technical validation and aggregation of the experts' answers to the primary and secondary research questions.

Data Records

The presented dataset is stored at Mendeley Data (https://data.mendeley.com/, https://doi.org/10.17632/7brkg-ztjdx.3)[21]; the individual files are described below.

Identification	Expertise	Major fields	Working years
Expert #1	Academist	Industrial engineering, Industry 4.0, servitization	33
Expert #2	Practitioner	Innovation and technology	29
Expert #3	Academist	Human-centered strategy for innovation, Industry 4.0	22
Expert #4	Practitioner	Research and development, innovation and servitization	20
Expert #5	Practitioner	Service engineering	19
Expert #6	Practitioner	Automation and digitalization in Industry 4.0, servitization	18
Expert #7	Academist	Sustainable product-service system, eco-innovation	14
Expert #8	Academist	Human-centered design, industrial design engineer	12
Expert #9	Practitioner	Digital manufacturing	10
Expert #10	Academist	Cyber physical systems, software engineering	7

Table 1. Expert profile.

(Expert Survey) Skill-rating questionnaires (.pdf). This file presents the expert survey with the pairwise skills-rating questionnaires in accordance with the AHP. There are a total of nine skills-rating questionnaires – representing the nine groups of design methods – for the pairwise comparison of five groups of employees (the design team members). Each expert (see Table 1) answered each skill-rating questionnaire to evaluate to what extent a design method (e.g., idea exploration) is preferred by a job role (e.g., executive officers) compared to another job role (e.g., marketing analysts) using a nine-point rating scale.

(Raw data) Skill-rating questionnaires through AHP (.xlsx). This file contains the expert responses to the skills-rating questionnaires. The first column of the file sheet contains the design skills for rating, including nine groups of design skills that represent the nine skills-rating questionnaires. The second column indicates the pairwise comparison among the five groups of design team members for each skills-rating questionnaire. The next 10 columns display the raw responses of the experts, whose identifications are matched with those in Table 1, using the nine-point rating scale of the pairwise comparisons. The 13th column stores the raw data in the form of CSV value strings used for their corresponding data inputs in R. The last column provides a summary of the data points and missing data points (NA): for a total of 862 data points, there are 38 missing datapoints (NA), that is, approximate 4.4% of the total data points.

(R codes) AHP analysis and result (.html). This file provides all the R codes[33] for executing the AHP algorithms[34] of the raw data (.xlsx). The missing data points (4.4% of the 862 data points) were also included without affecting the original dataset[35]. These R codes are presented in the four main sequenced sections: (i) R package preparation, (ii) data inputs, (iii) calculation of aggregated importance weights and (iv) calculation of the consistency ratios. The 'R package preparation' section presents the package instalment in the R environment to execute the AHP algorithms. The 'Data inputs' section indicates how the raw data (.xlsx) in the form of CSV value strings were inputted into R. The 'Calculation of aggregated importance weights' section indicates the aggregated results (see Table 2) of the expert decisions on the primary research question, namely 'who needs to know and/or practice what design methods, as design skills, to perform one or more design activities'. This aggregated result was also used to answer the two secondary questions: (i) who should be trained in what design methods; and (ii) how can these design methods be prioritized in building service capability. Finally, the 'Calculation of the consistency ratio' section presents the validation results for the consistency of the expert responses.

Technical Validation

The answer to the primary research question depends on the expertise of the surveyed experts; the expert panel did not need to be a representative sample for statistical inferences[30–32]. Therefore, the qualities of the expert panel, based on the expert selection criteria, were more critical for the analytical validity of this dataset than the number of participants. Moreover, the application of the AHP method to data analysis does not require a large sample size for statistical validity[17]; however, the expert responses represent subjective judgement based on the experts' expertise. Therefore, the consistency ratios had to be calculated to justify the consistency of the expert responses.

Based on the mathematical algorithms of the AHP[34], programed for its computation in the language of R[33], Table 2 summarizes the results of the analysis of the expert responses (the html file in the dataset[21]), including the consistency ratios and aggregated importance weights. The former indicates that all the values of the consistency ratios are not greater than 0.2, proving that the aggregated responses of the experts on these questionnaires are tolerably consistent[17,36]. This means that the interpretation of the aggregated importance weights is technically valid. The aggregated importance weights indicate that a group of design team members (e.g., executive officers or designers) needs to know and/or practice a group of design methods (e.g., idea exploration or prototyping methods) to a greater extent than other groups of design team members, with a total importance weight of 1. These aggregated importance weights reveal the answers to the primary and secondary research questions, which are further discussed in the next section.

Despite the rigorousness of this research, the authors acknowledge that there are limitations associated with pre-coded (closed) skills-rating questionnaires. These closed questionnaires in practice do not allow for other possible choices (design team members and design methods); this limitation of closed-ended questionnaires has also been acknowledged by other questionnaire-based research studies[16,37,38]. For instance, the expert or

	Aggregated importance weights[a]					Total weight	Consistency ratio (CR)[a]
	Executive officers	Marketing analysts	Finance analysts	Engineers and/or technicians	Designers		
Idea exploration	0.133	0.170	0.063	**0.257**	**0.377**	1	0.16
Participatory design	0.099	**0.256**	0.069	**0.194**	**0.382**	1	0.10
CX-centered methods	0.079	**0.307**	0.064	0.183	**0.366**	1	0.08
Idea clustering	0.190	**0.274**	0.097	0.143	**0.296**	1	0.20
Prototyping methods	0.100	0.105	0.054	**0.308**	**0.434**	1	0.11
Operations-centered methods	0.169	0.120	0.074	**0.329**	**0.308**	1	0.12
Business analytics	**0.260**	0.172	**0.353**	0.090	0.125	1	0.13
Engineering methods	0.128	0.076	0.059	**0.501**	**0.237**	1	0.11
Evaluation methods	0.102	**0.282**	0.144	0.169	**0.303**	1	0.17

Table 2. Aggregated importance weights and consistency ratio on each group of design methods with each group of design team members in accordance with AHP. [a]For aggregated importance weights, the experts consistently indicated two to three groups of design team members—whose importance weight values are higher than 0.19, dominating that of the other groups in the total importance weight of 1—should acquire a corresponding group of design methods (skill sets). The values of CRs—that are not greater than 0.2—prove the responses of the experts on these questionnaires are tolerably consistent[17,36]. These CRs allow for the valid interpretation on the analysis result. The transparent data and available codes of the research are provided in the dataset[21].

design practitioner may consider the role of the sales team in addition to the defined design team members (see Fig. 1) for advanced service designs. Therefore, the study findings need to be adapted to specific business contexts. Nevertheless, the validity of the expert responses was assessed to guarantee the technical validity of the analysis results, and an acceptable level of judgement bias was ensured based on the consistency ratios, as discussed above.

Usage Notes

To replicate this research, researchers and design practitioners should follow the procedures presented in the Methods section. Based on the research context, the content of the expert survey, which consisted of skills-rating questionnaires, and the expert selection criteria should be adopted. The methodology for collecting and analyzing datasets should follow the instructions documented in the Data Records section. The analysis of datasets can easily be accomplished reusing the R codes for the AHP algorithms (see the Code Availability section).

Researchers and design practitioners may reuse the analysis results of this research study's dataset (see Table 2) to look for practical applications by answering the research questions. First of all, for Table 2 the consistency ratios should not be greater than 0.2; if they are, the researchers should improve the survey design to ensure an acceptable level of consistency in the expert responses before further analysis. Subsequently, the aggregated importance weights indicate that the experts consistently indicated two to three groups of design team members – whose importance weight values are higher than 0.19, dominating those of the other groups in the total importance weight of 1 – need to know and/or practice a corresponding group of design methods (skill sets).

For the primary research question, for example in the skill set of 'idea exploration', the 'designers' and 'engineers and/or technicians' – whose importance weights are 0.257 and 0.377, respectively, in the total importance weight of 1 (see Table 2) – preferably need to master the skill set better than the other groups of design team members in terms of the aggregated perspectives of all surveyed experts. Based on these aggregated importance weights, the same reasoning is applicable to the rest of the design team members and groups of design methods.

Similarly, the answers to the two secondary research questions – (i) who should be trained in what design methods, and (ii) how can these design methods be prioritized in building service capability – are also based on the aggregated importance weights. For instance, in the skill set of 'participatory design', the 'designers', 'marketing analysts', and 'engineers and/or technicians' – who have the highest aggregated importance weights of 0.382, 0.256, and 0.194, respectively, in order – should be prioritized for the training of the skill set in the same order. As can be seen in Table 2, the skills of 'designers' are in the highest demand, except for the skill set of 'business analytics' (e.g., game theory, profit formula), which should be represented to a greater extent by 'executive officers' and 'financial analysts'. In addition to designers, 'engineers' should not only be competent in technical skills ('prototyping methods', 'operations-centered methods' and 'engineering methods'). They should preferably be trained to know the skill sets of 'idea exploration' and 'participatory design' used to understand both the tangible and latent requirements of customers.

In summary, the dataset and its analysis results enable researchers and design practitioners to build a transdisciplinary design team in which each group of design methods can be handled by two or three job roles, in the order of priority.

Code availability

The code availability for open access is given by the dataset[21]: *(R codes) AHP analysis and result.html*. These codes are written in R language (version 4.1.2, https://r-project.org) to input the raw data (.xlsx), run the AHP algorithm and produce the final result summarized in Table 2. For further description of the R codes, refer to the section Data Records.

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Author contributions

Ganix Lasa, Ion Iriarte: Conceptualization, Investigation, Methodology, Project administration, Supervision, Validation, Review & Editing. Hien Nguyen Ngoc: Data curation, Investigation, Methodology, Analysis, Visualization, Software, Writing - original draft. Ariane Atxa: Visualization design. Gorka Unamuno, Gurutz Galfarsoro: Evaluation, Consulting.

Competing interests

The authors declare no competing interests.

Additional information

Correspondence and requests for materials should be addressed to H.N.N.

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CHAPTER 5

Human-centred design for advanced services: A multidimensional design methodology

Brief summary

The present study is conducted in the context of advanced services, as a special case of PSS, that offer feature risk and revenue sharing agreements (use- and result-oriented PSS) with customers over the life-cycle service. The body of research in this field has witnessed the increasing expansion of review articles. To provide scientific contributions, this research was conducted to address the challenges posed by the current work. Specifically, human factors are not often addressed in the existing design methodologies even though design for advanced services requires human-centered thinking (Solem et al., 2021; Zheng et al., 2019). Therefore, a new design methodology must address the human-centric approach.

Furthermore, the literature highlights the essential relationship between the key design elements, which must be incorporated into a design methodology, as presented in Chapters 3 and 4. These design elements include: (1) the life-cycle service design (2) stakeholder networks; (3) new service design development methods; (4) design skills. Neglecting these design elements may lead to confusion in practice and result in ineffective implementation, ultimately resulting in the "service paradox" (Kwon et al., 2021; Ping et al., 2020).

Taking these into consideration, to design advanced services in an effective way, the second research question (RQ2) must be addressed: how are the key design elements and their relations incorporated in a single-view structure in accordance with a human-centric approach?

To address RQ2, the current study utilized an ontology-based approach (Hartmann & Trappey, 2020) to establish design knowledge through the relationships between the key design elements to form a novel multidimensional design methodology called DIMAND for advanced services. Specifically, DIMAND addresses the (1) life-cycle service design interrelated with other key design elements in a single-view structure with human-centric approach: (2) stakeholder networks; (3) new service development methods; (4) design skills. DIMAND offers a novel and holistic guideline for design practitioners and engineers to get coherence in all the life-cycle design processes by taking simultaneously these key design elements and their relations into account, making the design of advanced services more practical. As a result, the characteristics of DIMAND are addressed in four ways.

First, DIMAND addresses the life-cycle service design and interconnection among the design processes, facilitating the practitioners to keep the life-cycle perspective in mind and take process dependency and contingency planning in their design decisions.

Second, DIMAND is equipped with the complete piece of information about the stakeholder involvement, offering a complete guideline on how to oversee and plan “who will do what” across the life-cycle service design. Beyond the external stakeholders (e.g., customers, third parties), DIMAND encourages the practitioners to take the (direct and indirect) involvement and understanding of the internal actors (e.g., executive officers, marketers, engineers and technicians) into their design decisions, fostering the business culture perspective on advanced service design in addition to the market orientation.

Third, DIMAND is not only the life-cycle service design but it also shows how the design processes can be supported and implemented by the sets of new service development methods that are viable and proven in literature. This allows the design practitioners and engineers to be aware of a wide range of both service- and engineering-specific methods (e.g., service blueprints, TRIZ, Lean) that support transdisciplinary approach required for advanced service design.

Fourth, DIMAND also facilitates the practitioners to build the internal service capability ("who needs to know what") through these skill sets and makes the decision on the training priority under their business resource constraints. This capability building helps the company develop and nurture the transdisciplinary design team in which the skills and mindset from different fields function as an accelerator for the design of advanced services.

DIMAND is inspired by quality function deployment (Fan et al., 2019; Horvat et al., 2017) to formulate the interrelations among these four key design elements. DIMAND is formulated by the systematic reviews and structured analysis to identify and synthesize the commonalities, differences and patterns among the existing design methodologies in literature (Abdelmegid et al., 2020; Zabin et al., 2022). For validation, the usability of DIMAND was also assessed under the perspective of design practitioners and engineers through simplified system usability scale (D. Chang et al., 2019; Gopsill et al., 2015; Ya-feng et al., 2022), confirming its potential application and usage purpose within the context of advanced services.

Lastly, this study acknowledges that the conceptual methodology of DIMAND remains a limitation; this has been mitigated by the presentation of the supplemental information (Appendix B, Chapter 5), which provides guidance on how to implement DIMAND in practice. Therefore, future research should aim to overcome this limitation through a field implementation of DIMAND with longitudinal and multiple company cases. This field implementation can help to deploy and adapt DIMAND to fit the business context where internal stakeholders collaborate with researchers to develop advanced services. Through practical learning and experience during field implementation, DIMAND will be further refined through reflection in practice in each design process, leading to innovation practices for company cases in particular and lessons learned for DIMAND in general.

The full content of the present study is presented below.

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Human-centered design for advanced services: A multidimensional design methodology

Hien Ngoc Nguyen [a,*], Ganix Lasa [a], Ion Iriarte [a], Ariane Atxa [a], Gorka Unamuno [b], Gurutz Galfarsoro [c]

[a] Mondragon Unibertsitatea: Design Innovation Center (DBZ) - Faculty of Engineering, Loramendi, 4, 20500 Arrasate - Mondragón, Gipuzkoa, Spain
[b] IDEKO, member of Basque Research and Technology Alliance, Arriaga kalea, 2; E-20870 Elgoibar, Gipuzkoa, Spain
[c] UROLA, Urola Kalea, s/n - Apdo 3, 20230 Legazpi, Gipuzkoa, Spain

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ABSTRACT

Advanced services have caught the attention of industries and academics as a way to exploit new customer value propositions. However, the existing design methodologies for advanced services are limited to partially addressing one or some key design elements, hence causing confusion in practice. Moreover, human factors are not often addressed, even though the design for advanced services requires human-centered thinking. Aiming to advance the body of research, the current study aims to conceptually propose a multidimensional design methodology called DIMAND that captures the key design elements and their relations in a single-view structure in accordance with a human-centric approach. Specifically, DIMAND encapsulates the (i) life-cycle service design interrelated with other key design elements—(ii) stakeholder networks, (iii) new service development methods, and (iv) design skills—that must be considered to develop effective advanced service design. Based on a hybrid research design, DIMAND was conceptually developed through systematic reviews and structured analysis of existing design methodologies, as well as an elicitation of expert knowledge in the domain through the analytical hierarchy process (AHP). For validation, the average usability score of DIMAND as evaluated by 26 practitioners was 72.2, which falls into "excellence" on the simplified system usability scale (SUS), hence confirming its potential utility. As a result, DIMAND offers a novel and holistic guideline for design practitioners and engineers to obtain coherence in all the life-cycle design processes by simultaneously taking these key design elements and their relations into account, making the design of advanced services more practical.

1. Introduction

There is a prominent tendency in industries and academics to design for new value propositions that enable companies to increase market share, competitiveness and customer satisfaction. This tendency requires new business models that ask manufacturing companies to extend services through product–service systems (PSSs) for value creation [88]. These PSSs integrate tangible products with immaterial services and then provide customers with a complete solution [53]. The idea is to offer not only a product (by ownership), but also its performance (e.g., pay-*per*-performance) and usage (e.g., pay-*per*-use) as a bundle of products and services [98], enabling companies' value chains to be extended. Specifically, extensive work has been done to classify PSSs into typical groups [59,83]: product-oriented groups (paying for buying pure products); use-oriented groups (paying for use); and result-oriented groups (paying for performance result). Lately, Baines and W. Lightfoot [6] provided a delineation of use- and result-oriented groups as advanced services, which are a special case of PSSs, that offer feature risk and revenue sharing agreements with customers over the life cycle of the service. Therefore, these advanced services reflect new ways of value creation in diverse aspects [11,44,55,63]: smart connected products and services (smart PSSs), commercial gains (e.g., revenue growth through hybrid offerings), and compelling sustainability (e.g., efficiency in material and energy usage). Digital and smart technologies, for example, machine learning [22], internet of things technology and big data analytics [99], are enablers of these advanced services, whose value proposition is shaped by the alignment among service–product–technology solutions and market development [18,98].

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[*] Corresponding author.
E-mail addresses: nhneguyen@mondragon.edu (H.N. Nguyen), glasa@mondragon.edu (G. Lasa), iiriarte@mondragon.edu (I. Iriarte), ariane.atxa@alumni.mondragon.edu (A. Atxa), gunamuno@ideko.es (G. Unamuno), ggalfarsoro@urola.com (G. Galfarsoro).

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To design for these advanced services, a structural methodology is required to reflect the life-cycle service design and enable effective service delivery [52,53]. The design methodology also requires human actors to be placed in the center of design work [49], allowing for capturing customer latent needs and understanding stakeholder requirements [75]. To realize this, human-centered design (HCD)—that is a set of design principles, methods and tools and also a philosophy—enables design practitioners to co-create value propositions with people (or stakeholders) across the life-cycle design process [24,56,79]. Nevertheless, previous reviews have revealed that human factors are not often addressed, even though the design for advanced services requires human-centered thinking [80,98]. Specifically, Nguyen, Lasa and Iriarte [60] reviewed 43 case studies in HCD and PSSs in Industry 4.0; only 12 % of these studies made an effort to validate and confirm the important inclusions of human factors—background, age, gender, education, cultural influences, and privacy management—in design. The human-centric approach in design was also recently emphasized by Piera et al. [66], who called for the digitalization of new smart services (e.g., artificial intelligent supporting services) by accommodating social-technical factors: ageing, disabilities, inexperience, conform and wellbeing. These human factors are particularly important for consideration in advanced service design related to socio-technical systems (e.g., pilot cockpit), in which the time-stamp added value of human-contributed cognitive activities is required. Above all, design for advanced services demands a new HCD methodology to design new value propositions [42,80]. This demand establishes the scope of the current research, conceptually shaping the development of a new design methodology oriented to HCD for advanced services.

In addition, even though researchers have conceptualized different design methodologies for advanced services, these methodologies are limited to partially addressing one or some key design elements, which need to be methodically addressed in a new design methodology to develop effective advanced service design. Specifically, one of the first key design elements is the life-cycle service design, which is often missed in existing design methodologies that have been limited to the concept development stage [3,98]. Second, other design approaches did not fully consider stakeholder networks and their roles, although they play a vital role in value co-creation as a key design element [60,71]. Third, a lack of new service development methods—to support value co-creation with stakeholders (e.g., scenarios, stakeholders map and mood board)—has been witnessed in other design methodologies that solely applied engineering methods (e.g., quality function deployment, Kansei engineering) [21]. In a recent publication, Nguyen, Lasa and Iriarte [60] called for a future research direction where a new HCD methodology is required to systematically address and connect these key design elements: the life-cycle service design, stakeholder networks, and new service development methods. Fourth, the design skills required for design teams to practice design activities have rarely been studied, even though these design skills affect their performance in the design for advanced services [46,71]. A lack of consideration of these key design elements could cause confusion in practice, resulting in an ineffective implementation leading to a “service paradox” [52,67]. Therefore, the design for advanced services poses requirements for a new design methodology that is not only oriented to HCD, but also encapsulates the must-have relationship among these key design elements: (1) the life-cycle service design; (2) stakeholder networks; (3) new service development methods; and (4) design skills.

Taking these requirements into the research scope, to develop effective advanced service design, this study aims to conceptually propose a multidimensional design methodology that captures the key design elements and their relations in a single-view structure in accordance with a human-centric approach. This methodology is named DIMAND, which is an acronym of the first letter of its life-cycle service design phases (diagnose, identify, measure, analyze, navigate, and deliver); this is further explained in Section 4. Based on ontology as a formal representation of all concepts and their relations [34,36], DIMAND is conceptually developed to formulate design knowledge that expresses the relations of key design elements within the domain of advanced service design. In particular, on the opposite end of existing intuitive approaches, DIMAND aims to encapsulate the (i) life-cycle service design and its relations with other key design elements—(ii) stakeholder networks, (iii) new service development methods, and (iv) design skills—that must be considered to develop effective advanced service design. As a structural design approach, DIMAND wants to help design teams govern the entire life-cycle service design by simultaneously considering these key design elements and their relations, hence making the design of advanced services more practical. This is realized by conceptually building DIMAND on a hybrid research design that takes advantage of (i) the body of knowledge in the literature through systematic reviews and *meta*-analyses, (ii) the elicitation of expert expertise through the analytical hierarchy process (AHP), and (iii) the usability assessment given by design practitioners and engineers through the simplified system usability scale (SUS).

The present work is organized as follows: Section 2 discusses the key design elements required for the design methodology. Section 3 presents the literature on the hybrid research design used to develop DIMAND. In Section 4, we present the new multidimensional design methodology for advanced services (DIMAND). Section 5 highlights the potential utility of DIMAND from the perspective of design practitioners. Section 6 provides the concluding remarks. Finally, these main sections are accompanied with the appendices (A and B) and research data [61] as supplementary information that enriches the transparency of the research results.

2. Framing key design elements required for advanced service design

According to the International Organization for Standardization [41], HCD incorporates human factors and ergonomics knowledge and techniques to make systems usable. This definition is broadened in the context of Industry 4.0 in which HCD offers a multidimensional (e.g., design artefacts, service solutions to ethical and legal issues) and transdisciplinary approach (e.g., physical, cognitive and social factors) in various design fields [60]: PSSs, user-centered design, human-in/on-the-loop, human–machine interface, and human-robot collaboration. These human-centric approaches are essential for exploring complex interdependencies of human and non-human actors (e.g., digital interfaces, smart devices and machines) in cyber-physical systems; hence, they can help in paving the way for understanding methodologically both functional and non-functional requirements [19,28]. Although functional requirements are technically evaluated or judged, non-functional requirements (e.g., service level agreement, user usability) are hardly defined without a human-centric approach [28,43]. The lack of consideration of these non-functional requirements could cause design problems: unexpected service behavior and even extensive redesign work. In the context of real-time supporting services, Kong et al. [48] called the design problems in using smart digital wearable systems (e.g., virtual and mixed reality) as user frustration or “key pain spots”. To alleviate design problems, HCD needs to be considered to help design practitioners in focusing on human factors and diversity to gain critical design requirements and feedback. These design requirements may range from human use and performance (e.g., postural comfort, physical ergonomics) [14,65] to human perception and cognition (e.g., mental stress, emotional stress, agreeableness, conscientiousness, neuroticism, openness) [70,92]. In the context of PSSs, Sierra-Pérez et al. [79] applied HCD to capture the stakeholder requirements in both functional requirements (e.g., scooter battery levels, scooter travel time) and non-functional requirements (e.g., trustworthiness, usefulness) for design. Similarly, Bu et al. [10] and Chang et al. [17] placed people (users and stakeholders) at the center of the requirements in their design approaches for user-centric smart PSSs. To confirm the role of HCD, Zheng et al. [98] systematically reviewed 97 studies and relevant works related to smart PSSs before coming to the conclusion that a human-centric approach must be addressed in a new design methodology. This conclusion shapes the scope of the current study, which aims to develop the new proposed multidimensional design methodology (DIMAND) oriented to HCD for advanced services.

In addition, the most recent literature reviews have revealed the key design elements that need to be addressed in a design methodology to develop effective advanced service design. Hence, the present study aims to conceptually develop DIMAND so that it is not only oriented to a human-centric approach, but also structured to systematically cover these key design elements. Based on ontological knowledge representation [36], Fig. 1 presents the formal representation of these key design elements and their relations, that is, what must be addressed in DIMAND.

First, Marilungo et al. [57] and Vasantha et al. [87] considered the life-cycle service design to be one of the key design elements. They analyzed different design approaches (e.g., design for PSSs, service engineering) in detail and then drew the conclusion that some design phases (e.g., planning and design) were well addressed; however, others (e.g., implementation, monitoring, feedbacks among phases) were vaguely defined. Agreeing with this conclusion, Agher et al. [3] and Song and Sakao [81] also carried out extensive review works before concluding that there is a lack of systematic methodical support covering the entire life-cycle service design. Recently, Carrera-Rivera et al. [15] systematically reviewed 53 studies in the context of smart PSSs and pointed out that those studies using a human-centric approach are very limited to the design phases instead of the life-cycle service design. Therefore, the design for effective advanced services requires life-cycle consideration encompassing all life-cycle phases in which design processes are defined to execute their corresponding phases [57,87,91]: planning and design, implementation and monitoring, product/service usage, and feedback loops between phases. Therefore, the first class of key design elements is the life-cycle service design, which needs to be expressed in DIMAND to cover the life-cycle design phases associated with design processes.

Second, in addition to the life-cycle service design, Richter et al. [71] analyzed 42 existing design methodologies for PSSs, concluding that these methodologies did not fully address the key design element: the actors and partners (stakeholders networks) and their engagement. Agreeing with this finding, Nguyen, Lasa and Iriarte [60] analyzed 43 existing design methodologies in HCD and PSSs in Industry 4.0, confirming the key design decisions (success factors) for effective design: (i) stakeholder networks and (ii) their involvements in each life-cycle design phase. The stakeholder networks are characterized by both internal stakeholders (e.g., design managers, manufacturing and maintenance staff) and external stakeholders (e.g., customers, third-party suppliers) whose diversity in interests and expectations needs to be respected and analyzed to comprehend the impact of stakeholder engagement at different life-cycle design phases. The engagement modes are defined by three levels of involvement: (i) an informative level, in which stakeholders only provide and receive design information; (ii) a consultative level, in which they comment on pre-define design scenarios; and (iii) a participative level, in which they make influencing decisions on a design process and outcome [60,77]. Thus, to develop effective advanced service design, DIMAND must cover this second class of key design elements: stakeholder networks that address both internal and external stakeholders, and their involvement in different life-cycle design phases. This relation between stakeholder networks and life-cycle service design is denoted as R1 in Fig. 1.

The third class of key design elements represents new service development methods emphasized by Jing-chen Cong et al. [21]. The authors carried out a systematic review of the design approaches since the coining of the term PSSs to May 2020, highlighting limitations in studies focusing on adopting engineering methods—such as TRIZ as creative problem-solving techniques [53], quality function deployment [67] or Kansei engineering [17]—instead of new service development methods. Recently, Nguyen, Lasa and Iriarte [60] also highlighted the key role of these methods, including engineering and non-engineering methods, in transdisciplinary design (e.g., physical, cognitive and social factors) required for advanced services. For instance, non-engineering methods (e.g., participatory design, interviews) can help designers focus on human diversity to gain critical design requirements, while the engineering methods (e.g., Kano model) enrich the prioritization and segmentation of these design requirements. Accordingly,

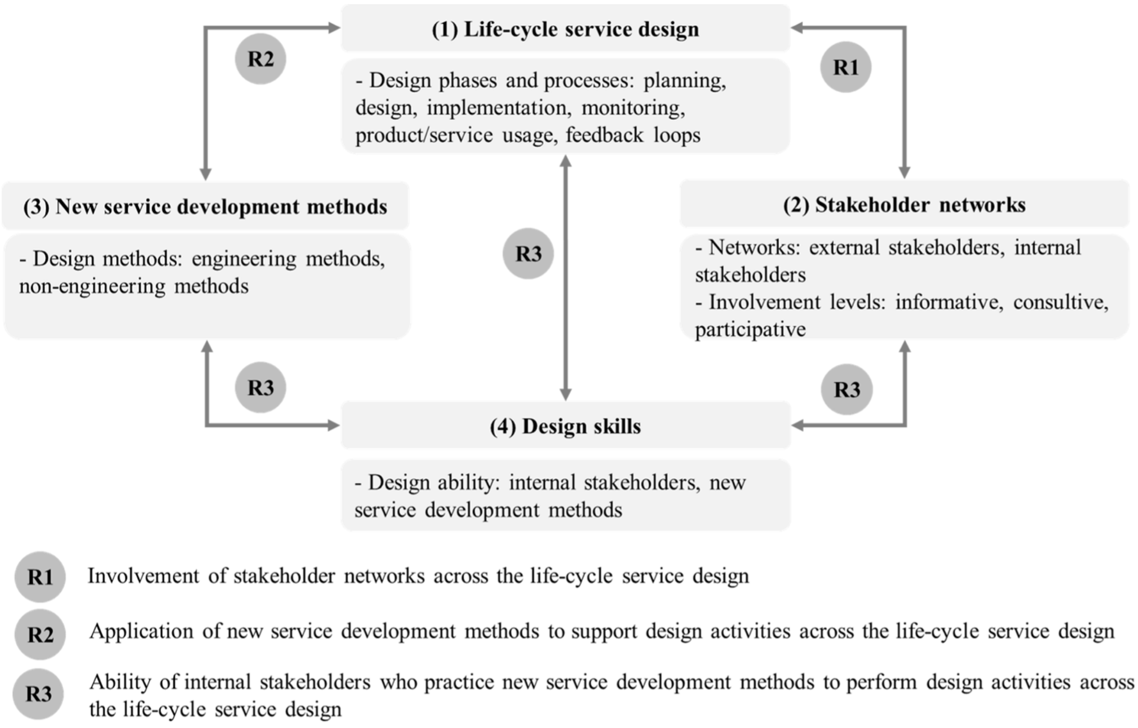


Fig. 1. Formalization of the key design elements and their relations for advanced service design.

DIMAND must take into account these new service development methods to support transdisciplinary design activities across different life-cycle design phases. This relationship between new service development methods and life-cycle service design is denoted as R2 in Fig. 1.

Finally, the fourth class of key design elements accounts for the actors' design skills: the ability of an actor who practices particular new service development methods to perform design activities (e.g., market research, design for agile prototyping). These design skills have rarely been addressed in the literature; this limitation was emphasized by Richter et al. [71]. The authors stated that the existing methodologies did not fully address the design skills required for design practitioners, who are typically internal stakeholders (e.g., designers, engineers, manufacturing and maintenance staff) and responsible for design activities and outcomes. The consideration of design skills in a design methodology is required, as indicated by Baines et al. [5] and Ingo Oswald Karpen et al. [46], who demonstrated that design skills are the key factors influencing key performance in advanced service design. Agreeing with this point, Spreitzer et al. [82] requested that company staff (internal stakeholders) need to be equipped with the proper skills to enable them understand how their work performance is carried out and developed. Thus, training on these proper skills helps companies enhance their sustainable development. This also means that the importance of anyone directly or indirectly involved in the making of products and/or services is embraced, hence developing a business culture on advanced service design instead of only market orientation [27,29]. Therefore, DIMAND also incorporates design skills—the ability of internal stakeholders who practice new service development methods to perform design activities across the life-cycle service design—to make the design of advanced services more practical. This relation among design skills, stakeholder networks (internal stakeholders), new service development methods and life-cycle service design is denoted as *R*3 in Fig. 1.

In summary, even though some studies have defined design methodologies, they only partially covered one or some key design elements for advanced services, which can cause confusion in practice. Hence, to develop effective advanced service design, the new multidimensional design methodology for advanced services (DIMAND) is conceptually proposed to capture the key design elements and their relations (Fig. 1) in a single-view structure, here in accordance with a human-centric approach. This structure aims to facilitate design practitioners and engineers to govern the entire life-cycle service design by simultaneously considering these key design elements and their relations, making the design of advanced services more practical. This is realized by utilizing a hybrid research design.

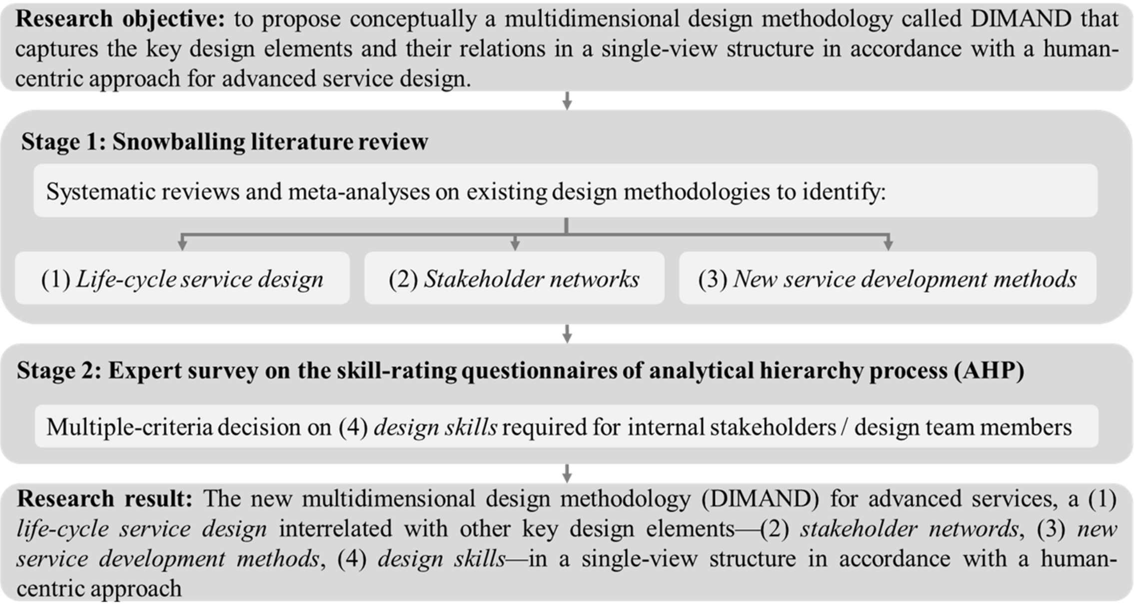
3. Research design

In the present study, the new multidimensional design methodology for advanced services (DIMAND) has been designed to encompass the interconnected key design elements (see Fig. 1). Fig. 2 shows two development stages of DIMAND, which are presented in the following subsections.

3.1. Snowballing literature review (stage 1)

First, we used logic to formulate design knowledge through a structured analysis of the different design methodologies in the literature [37]. The logic we followed was one of systematic reviews and *meta*-analyses conducted to identify and synthesize the relevant studies, which presents the design methodologies, frameworks or models oriented to a human-centric approach for advanced services. The analysis helped in identifying the patterns and synthesizing the key design elements (Fig. 1)— that were extracted from the identified studies—through the affinity method, which is known as the KJ method [4]; we could then structure them to form DIMAND. To realize this synthesis, we applied a snowballing literature review (SLR) so that the interrelated papers referenced and/or cited among them were systematically included [93]. Originating from evidence-based software engineering first coined by Kitchenham et al. [47], SLR has been accepted in engineering research, particularly for software engineering and advanced engineering informatics [1,97]. In addition, the implementation of a SLR can reduce the noise in searching for papers when compared with other systematic review methods, such as search strategies in databases [90]. Therefore, we executed the SLR procedure with the guidelines proposed by Wohlin [90] and presented in Fig. 3.

To conceptually propose a multidimensional design methodology (DIMAND) in accordance with a human-centric approach for advanced service design, the first step was to identify relevant papers whose research objective was to present a design methodology oriented to a human-centric approach for advanced services. Therefore, Therefore, there were three fundamental keywords: "human-centric", "methodology" and "advanced services"; however, scholars use disparate terms to



Research objective: to propose conceptually a multidimensional design methodology called DIMAND that captures the key design elements and their relations in a single-view structure in accordance with a human-centric approach for advanced service design.

Stage 1: Snowballing literature review

Systematic reviews and meta-analyses on existing design methodologies to identify:

(1) *Life-cycle service design*

(2) *Stakeholder networks*

(3) *New service development methods*

Stage 2: Expert survey on the skill-rating questionnaires of analytical hierarchy process (AHP)

Multiple-criteria decision on (4) *design skills* required for internal stakeholders / design team members

Research result: The new multidimensional design methodology (DIMAND) for advanced services, a (1) *life-cycle service design* interrelated with other key design elements—(2) *stakeholder networks*, (3) *new service development methods*, (4) *design skills*—in a single-view structure in accordance with a human-centric approach

Fig. 2. Development stages of the new proposed multidimensional design methodology for advanced services (DIMAND).

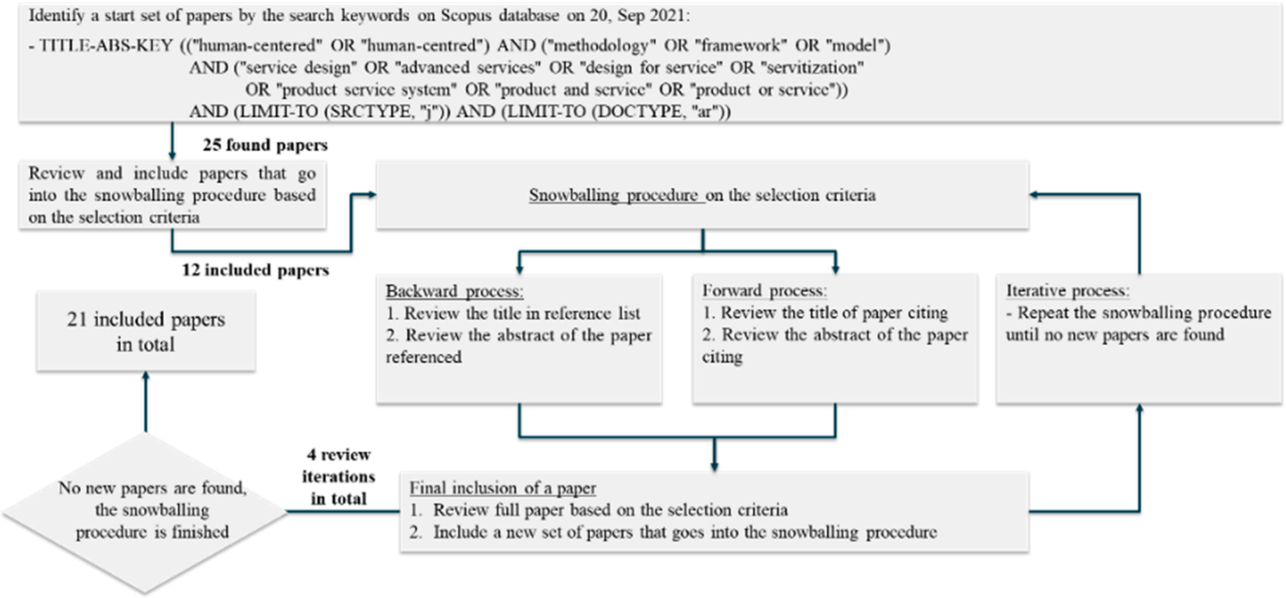


Fig. 3. A process flow of snowballing literature review.

describe these in the research community. First, the term “human-centric” has been well searched by the term “human-centered” to look for papers related to HCD in various contexts (e.g., human factors, person-centered solutions, human-centered manufacturing) [31,60,64]. Second, the term “methodology” has been frequently used together with “framework” or “model” in the context of PSSs [71]. Finally, papers related to “advanced services” can typically be found by using different but related terms, such as “product-service” and “servitization” [8,69], because the design for advanced services is a special case of PSSs [6]. As a result, the search string used to look for relevant papers was the connection of the terms associated with stemming: “human-centered”, “methodology”, “advanced services”, “product-service”, “servitization”. In addition, SLR is less sensitive to search strings and/or keywords compared with using other systematic review methods (e.g., search strategies in databases); SLR mainly replies on the interrelated papers actually referenced and/or cited among them [90]. In conclusion, the search string is reasonable for use in accordance with the procedure of SLR (Fig. 3).

As mentioned in Fig. 3, the first set of relevant papers (seeds) were searched using Scopus—through papers’ titles, abstracts and keywords—because a single database is only required because a snowballing review depends on the referenced papers. These initial studies were evaluated and included by the following inclusion criteria: a full-text English and journal paper presenting a design methodology, framework or model oriented to a human-centric approach for advanced services. As a result, 25 papers were identified and evaluated against the inclusion criteria, resulting in 12 papers. These papers were selected for performing the snowballing procedure (the backward and forward process), in which their references and citing papers were reviewed against the selection criteria to identify new relevant papers. By following this approach, the completeness and replication of the SLR ensured the sufficient extraction of relevant studies, resulting in 21 included papers through four review iterations in total.

The design methodologies proposed by these 21 included papers were objectively analyzed to obtain the most information about the key design elements (Fig. 1) that were structured to form DIMAND. The detailed information extracted from each analyzed design methodology is recorded in Appendix A. Based on the analysis results, we captured three key design elements: (1) life-cycle service design, (2) stakeholder networks and (3) new service development methods. However, we found a prominent void in the literature where none of the analyzed papers addressed the last design element: (4) design skills. This motivated Nguyen, Lasa, Iriarte, Atxa, et al. [62] to conduct the below stage with an expert survey (Fig. 2) to fill this void.

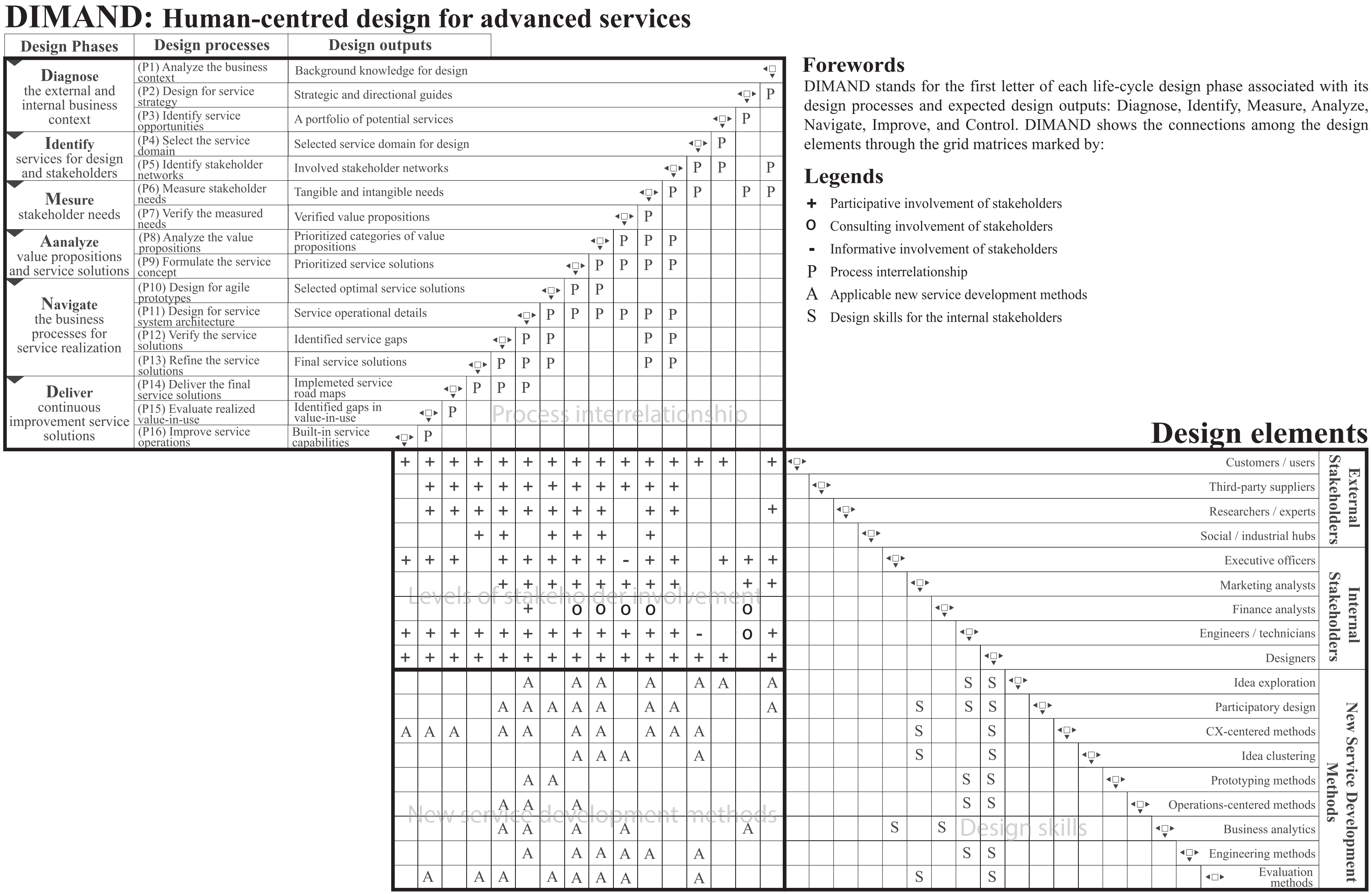
3.2. Expert survey on skill-rating questionnaires of AHP (stage 2)

Knowledge representation (Fig. 1) related to design skills can be formulated into a rational question: “Who” (internal stakeholders or design teams, e.g., designers, manufacturing engineers) needs to practice “what” new service development methods (e.g., workshop techniques), here as design skills, to perform design activities (e.g., to understand customer nonfunctional requirements)? Based on expert elicitation as a methodological approach for formalization of knowledge [37], Nguyen, Lasa, Iriarte, Atxa, et al. [62] addressed this question by applying the AHP because the AHP elicits and aggregates expert responses to a question through an expert survey.

Fundamentally, based on the AHP, the expert survey contained skill-rating questionnaires in the form of pairwise comparison used to ask the experts to grade the importance weights of all design teams (elements or alternatives) on the acquisition of new service development methods. These design teams were independent, as required by Saaty [72]. Given

Table 1
Expert profile [62].

Identification	Expertise	Major fields	Working years
Expert #1	Academist	Industrial engineering, Industry 4.0, servitization	33
Expert #2	Practitioner	Innovation and technology	29
Expert #3	Academist	Human-centered strategy for innovation, Industry 4.0	22
Expert #4	Practitioner	Research and development, innovation and servitzation	20
Expert #5	Practitioner	Service engineering	19
Expert #6	Practitioner	Automation and digitalization in Industry 4.0, servitization	18
Expert #7	Academist	Sustainable product-service system, eco-innovation	14
Expert #8	Academist	Human-centered design, industrial design engineer	12
Expert #9	Practitioner	Digital manufacturing	10
Expert #10	Academist	Cyber physical systems, software engineering	7



DIMAND: Human-centred design for advanced services

Process interrelationship

Design Phases	Design processes	Design outputs	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	P14	P15
Diagnose the external and internal business context	(P1) Analyze the business context	Background knowledge for design															
	(P2) Design for service strategy	Strategic and directional guides	P														
	(P3) Identify service opportunities	A portfolio of potential services		P													
Identify services for design and stakeholders	(P4) Select the service domain	Selected service domain for design			P												
	(P5) Identify stakeholder networks	Involved stakeholder networks	P		P	P											
Mesure stakeholder needs	(P6) Measure stakeholder needs	Tangible and intangible needs	P	P		P	P										
	(P7) Verify the measured needs	Verified value propositions						P									
Aanalyze value propositions and service solutions	(P8) Analyze the value propositions	Prioritized categories of value propositions					P	P	P								
	(P9) Formulate the service concept	Prioritized service solutions					P	P	P	P							
Navigate the business processes for service realization	(P10) Design for agile prototypes	Selected optimal service solutions								P	P						
	(P11) Design for service system architecture	Service operational details					P	P	P	P	P	P					
	(P12) Verify the service solutions	Identified service gaps					P	P				P	P				
	(P13) Refine the service solutions	Final service solutions					P	P				P	P	P			
Deliver continuous improvement service solutions	(P14) Deliver the final service solutions	Implemeted service road maps											P	P	P		
	(P15) Evaluate realized value-in-use	Identified gaps in value-in-use														P	
	(P16) Improve service operations	Built-in service capabilities															P

Design elements

Levels of stakeholder involvement

	Design elements	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	P14	P15	P16
External Stakeholders	Customers / users	+		+	+	+	+	+	+	+	+	+	+	+	+	+	+
	Third-party suppliers					+	+	+	+	+	+	+	+	+	+	+	
	Researchers / experts	+				+	+		+	+	+	+	+	+	+	+	
	Social / industrial hubs						+		+	+	+		+	+			
Internal Stakeholders	Executive officers	+	+	+		+	+	-	+	+	+	+	+		+	+	+
	Marketing analysts	+	+			+	+	+	+	+	+	+	+				
	Finance analysts		o				o	o	o	o		+					
	Engineers / technicians	+	o		-	+	+	+	+	+	+	+	+	+	+	+	+
	Designers	+		+	+	+	+	+	+	+	+	+	+	+	+	+	+

New service development methods

	Design elements	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	P14	P15	P16
New Service Development Methods	Idea exploration	A		A	A		A		A	A		A					
	Participatory design	A				A	A		A	A	A	A	A				
	CX-centered methods				A	A	A		A	A		A	A		A	A	A
	Idea clustering				A			A	A	A							
	Prototyping methods										A	A					
	Operations-centered methods									A		A	A				
	Business analytics		A					A		A		A	A				
	Engineering methods				A		A	A	A	A		A					
	Evaluation methods				A			A	A	A	A		A	A		A	

Design skills

	Executive officers	Marketing analysts	Finance analysts	Engineers / technicians	Designers
Idea exploration				S	S
Participatory design		S		S	S
CX-centered methods		S			S
Idea clustering		S			S
Prototyping methods				S	S
Operations-centered methods				S	S
Business analytics	S		S		
Engineering methods				S	S
Evaluation methods		S			S

Forewords

DIMAND stands for the first letter of each life-cycle design phase associated with its design processes and expected design outputs: Diagnose, Identify, Measure, Analyze, Navigate, Improve, and Control. DIMAND shows the connections among the design elements through the grid matrices marked by:

Legends

- **+** Participative involvement of stakeholders
- **o** Consulting involvement of stakeholders
- **-** Informative involvement of stakeholders
- P Process interrelationship
- A Applicable new service development methods
- S Design skills for the internal stakeholders

Fig. 4. A multidimensional design methodology for advanced services (DIMAND). The supplementary information (Appendix B) describes how DIMAND works in practice.

n design teams, that is, $D_1, \cdots, D_n$, the expert decides the relative importance r_{bd}—on a 9-point rating scale—indicating the importance of D_b relative to that of D_d to acquire a new service development method as a design skill. If these importance weights given by the expert are denoted as $w_1, \cdots, w_n$ corresponding to each design team member, then r_{bd} is the ratio of $\mathrm{w}_b/\mathrm{w}_d$. This formulates the reciprocal matrix of pairwise ratios:

$$D = \begin{bmatrix} \mathrm{w}_1/\mathrm{w}_1 & \cdots & \mathrm{w}_1/\mathrm{w}_n \\ \vdots & \ddots & \vdots \\ \mathrm{w}_n/\mathrm{w}_1 & \cdots & \mathrm{w}_n/\mathrm{w}_n \end{bmatrix} \qquad (1)$$

The experts who gave the importance weights through the expert survey were recruited based on their qualities rather than selecting a large and representative sample size to have a statistical inference (S. [54,68]. Thus, Nguyen, Lasa, Iriarte, Atxa, et al. [62] recruited 10 (industrial and academic) recognized experts, whose profiles are presented in Table 1; their disciplines were diverse, including HCD, industrial engineering and automation, servitization, business model and sustainable PSSs. As a result, the inputs for the expert survey were transdisciplinary. Through AHP algorithms, Nguyen, Lasa, Iriarte, Atxa, et al. [62] used the R language to compute all the reciprocal matrices of pairwise ratios whose data originated and were collected from the recruited experts responding to the expert survey. The AHP analysis results are presented in Section 4.4.

At the end of stage 2 (Fig. 2), we fully identified the first three key design elements—(1) life-cycle service design, (2) stakeholder networks and (3) new service development methods—from the SLR and then extracted the last one—(4) design skills—from the expert survey using the AHP [62]. These key design elements were then ready to be structured to form DIMAND, which can integrate and interlink these key design elements in a single-view structure in accordance with the human-centric approach.

4. Novel multidimensional design methodology for advanced services (DIMAND)

As mentioned in Section 2, the weakness was often addressed in the literature, where the existing methodologies did not fully comprehend—or just partially covered—the key design elements. One way to overcome this weakness is to formulate and map design knowledge through ontology (Fig. 1) that can present the relations among the key design elements within the domain of advanced services. This design knowledge can be detailed through a grid matrix—that has various applications, such as quality function deployment [26,40], to show correlation relationships among multiple elements—for its implementation in practice. Therefore, we customized this correlation matrix so that these design elements would be interconnected to form DIMAND as a single and multidimensional structure, as presented in Fig. 4. This structure can enable design practitioners and engineers to oversee the life-cycle service design (Section 4.1), which possesses the two-dimensional (back and forth) interrelationship among design elements: stakeholder networks (Section 4.2), new service development methods (Section 4.3) and design skills (Section 4.4). The following subsections present how DIMAND (Fig. 4) was formed through the two stages of the research design (Fig. 2) and how it works.

4.1. *The life-cycle service design*

As the first part of knowledge representation (Fig. 1), life-cycle service design must cover all life-cycle design phases and processes: planning and design, implementation and monitoring, product/service usage, feedback loops between phases. This requirement governs how the included studies were analyzed to synthesize the life-cycle service design. Based on the requirement and procedure of SLR presented in Section 3.1, we identified, analyzed and tabulated the 21 included studies, presenting their proposed HCD methodologies (see Appendix A). Based on this analysis, not all the analyzed design methodologies fully proposed life-cycle design phases and processes; the differences and omissions were very apparent among them. Specifically, Hartono [38] proposed a design methodology whose first design process was the "selection of the service domain"—to select airport service attributes (e.g., waiting rooms, staff friendliness) for service design—and subsequently "measurement of Kansei response"—to measure the feelings of customers about these service attributes. Instead of beginning with the "selection of the service domain", Camussi et al. [13] and Schiro et al. [76] proposed their own methodologies starting with "awareness-raising actions" in the context of public healthcare and "work system analysis" for healthcare information systems, respectively. Even though these design processes had different descriptions—"measurement of Kansei response", "awareness-raising actions", and "work system analysis"—and were applied in different contexts, their objective or outputs shared mutual facts: to "measure stakeholder needs" for design (e.g., understanding of customer needs and desires). By following this pattern of finding these mutual facts among the differences, the affinity analysis—known as the KJ method [4]—was applied to synthesize the analyzed design methodologies (Appendix A) in terms of design phases, design processes and outputs.

As a result, Table 2 shows the complete synthesis of the various research contexts of research (e.g., airport, media and healthcare) that appeared in almost all empirical studies (17 out of 21 studies). This formed the new HCD methodology, DIMAND, which stands for the first letters of six life-cycle service design phases: (i) *diagnose* the external and internal business context, to capture market opportunities and take the business capabilities (e.g., strategies, competitive advantage) into account; (ii) *identify* services for design and stakeholders, to select the service domain associated with its stakeholder networks; (iii) *measure* stakeholder needs, to capture tangible and intangible needs that are translated into value propositions; (iv) *analyze* value propositions and service solutions, to investigate the value propositions and translate them into service solutions; and (v) *navigate* the business processes for service realization, to direct the business resources and processes to design for these service solutions; (vi) *deliver* continuous improvement service solutions, to launch the service solutions with continuous-improvement service operations.

Therefore, the left pillar of DIMAND (Fig. 4) addresses HCD for advanced services, including the consecutive and interlinked design phases associated with design processes and outputs, forming the life-cycle service design, whose detailed description is presented in the supplementary information (Appendix B). This life-cycle service design includes from the *diagnose* and *identify* phase (planning), the *measure* and *analyze* phase (design), the *navigate* phase (implementation and monitoring), and the *delivery* phase (product/service usage). Moreover, the interrelationship of all design processes—here reflecting the feedback loops among them—is also displayed by the grid matrix, whose cells are marked by "P"; otherwise, there is no relationship addressed among them by the reviewed papers. Specifically, Acklin [2] and Iriarte et al. [42] paid attention to the *diagnose* and *identify* phase. First, Acklin [2] proposed a design methodology whose the first design process was to "analyze the business context" for the acquisition of "background knowledge for design": to understand what a company has learned so far and its business ecosystem (e.g., markets, customer trends). This understanding can enable the company to "design for service strategy" (e.g., communication and brand strategies). Second, Iriarte et al. [42] highlighted their design methodology whose starting design process was to "analyze the business context" by taking a snapshot of a detailed investigation of the business: competitive advantages and potential value propositions for advanced services in the machinery industry. According to the authors, this investigation can help the company properly "identify stakeholder networks": key customer staff responsible for the purchase of the solution on offer (e.g., top managers, technicians, and operations personnel), and internal stakeholders (e.g., quality manager, operations manager, product manager, technicians). Instead

Table 2
The synthesis of the life-cycle service design, as extracted from Appendix A.

Author(s)	Year	Research type	Context	DIMAND methodology[a]															
				Diagnose the external and internal business context			Identify services for design and stakeholders		Measure stakeholder needs		Analyze value propositions and service solutions		Navigate the business processes for service realization				Deliver continuous improvement service solutions		
				Analyze the business context	Design for service strategy	Identify service opportunities	Select the service domain	Identify stakeholder networks	Measure stakeholder needs	Verify the measured needs	Analyze the value propositions	Formulate the service concept	Design for agile prototypes	Design for service system architecture	Verify the service solutions	Refine the service solutions	Deliver the final service solutions	Evaluate realized value-in-use	Improve service operations
Hartono [38]	2020	Empirical	Airport services				X		X	X	X	X			X				
Camussi et al. [13]	2020	Empirical	Public healthcare						X		X	X	X						
Schiro et al. [76]	2020	Empirical	Health information systems						X		X	X	X	X	X		X		
Papazoglou et al. [64]	2020	Empirical	Laser and sheet metal machinery						X	X	X	X		X	X	X			
Grenha Teixeira et al. [33]	2019	Empirical	Health information systems						X		X			X	X	X			
Yu & Sangiorgi [96]	2018	Empirical	Digital services						X		X	X	X	X			X	X	X
Yu [95]	2018	Empirical	Library services						X		X								
Iriarte et al. [42]	2018	Empirical	Railways and sheet metal machinery	X				X	X		X	X	X	X	X				
Costa et al. [25]	2018	Empirical	Laboratory equipment					X	X		X	X	X	X	X	X	X		
Ueda et al. [86]	2018	Conceptual	ICT services and products						X		X	X	X		X				
Grenha Teixeira et al. [32]	2017	Empirical	Media and healthcare						X			X	X	X	X				
Salgado et al. [73,74]	2017a 2017b	Empirical	Public healthcare	X					X		X	X	X		X	X	X	X	
Cha et al. [16]	2017	Empirical	ICT car services						X		X	X	X	X	X	X			
Chew [18]	2016	Conceptual	Commercial services		X				X	X	X	X		X					
Kumar & Maskara [50]	2015	Empirical	Health information systems						X		X	X	X						
Kumar et al. [51]	2014	Empirical	Public healthcare						X		X	X	X						
Ueda [84,85]	2013 2009	Conceptual	ICT services			X	X		X		X	X	X	X	X				
Acklin [2]	2010	Conceptual	Undefined	X	X	X		X						X			X	X	X
Johnson et al. [45]	2005	Empirical	Health information systems				X		X		X	X	X		X	X			

[a] DIMAND is the acronym of the first letter of life-cycle service design phases: diagnose, identify, measure, analyze, navigate, and deliver. Appendix B presents each design phase in detail.

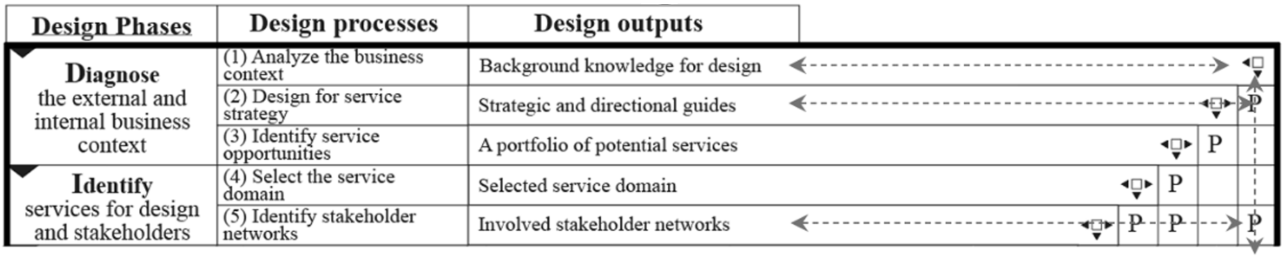


Fig. 5. An illustration of process interdependency. A cutting plane of DIMAND (Fig. 4) that exemplifies how the design processes are a two-dimensional interrelationship through the grid matrices, which can be seen by reading the path of the two-directional dotted arrows as an example. This reading pattern is applicable to the rest of the connections among the design elements in DIMAND.

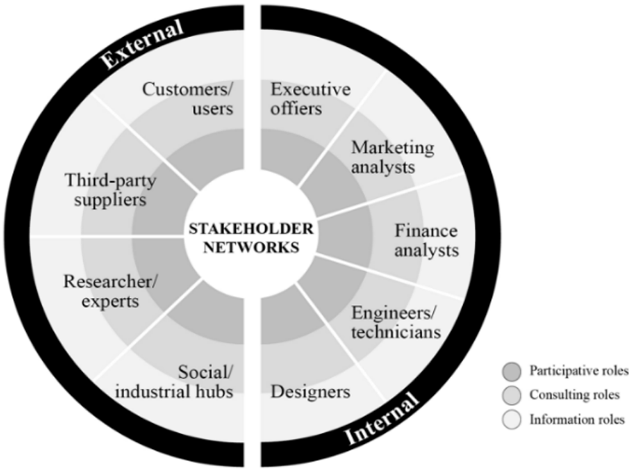


Fig. 6. The synthesis of stakeholder networks, extracted from Appendix A. Each stakeholder can take or exchange among the participatory roles, consulting roles or information roles in the different stages of life-cycle service design.

of focusing on the *diagnose* and *identify* phase, Yu [95] focused only on the *measure* and *analyze* phase (design). The author proposed a HCD methodology whose the starting design task was to “measure stakeholder needs” in both functional and non-functional requirements of students in terms of a library service (e.g., experiences, opinions, user perception). Subsequently, the measured requirements were the design inputs used to “analyze the value propositions” according to user contexts, such as physical conditions, technical capabilities, and cognitive links among product attributes, consequences, and goals.

Process interdependencies (feedback loops) among these design processes is symbolized by “P” through the grid matrix in DIMAND; this is exemplified in Fig. 5, which shows the feedback loops among the design processes: “analyze the business context”, “design for service strategy”, and “identify stakeholder networks”.

These interdependencies or feedback loops among design processes have not been commonly addressed in the literature; however, they support the practitioners to cross track the design outcome among these design processes because the outcome of a design process may affect that of another design process. Above all, DIMAND addresses the life-cycle service design and interconnection among the design processes (“P”), facilitating design practitioners to keep the life-cycle perspective in mind and take process dependency and contingency planning into their design decisions.

4.2. Stakeholder networks

For the second part of knowledge representation (Fig. 1), stakeholder networks must consider both internal and external stakeholder networks, and their involvement levels—an informative level, a consultative level, a participative level—across the life-cycle service design. This consideration governs how the included studies were analyzed to synthesize the stakeholder networks. Similar to the synthesis of the life-cycle service design, the design element of the stakeholder networks has been built by extracting and synthesizing the “Stakeholders” across the design processes, here as addressed by the analyzed design methodologies (Appendix A). Fig. 6 shows the synthesis of the stakeholder networks, revealing broad participation of both internal and external stakeholders. Moreover, we classified the stakeholder roles into three levels of involvement—informative (“-”), consultative (“o”), and participative (“+”)—across life-cycle design processes. Specifically, the informative stakeholders can take passive roles in the provision and receipt of design information, while consultative stakeholders consult design actions and solutions. The participative stakeholders co-create and engage with their decisions on the design process.

The top of the right pillar of DIMAND (Fig. 4) embeds the stakeholder networks. These stakeholder networks are connected with the life-cycle service design (the left pillar) through the same grid matrices of DIMAND, hence realizing the relation between them (R1 in Fig. 1). By doing this, two design decisions related to the involvement of stakeholders can be made: (i) who will be involved in which specific design process and/or which design process asks for the participation of whom and (ii) what the level of involvement for each stakeholder in the according design process. The answer to these two questions is given by the grid matrices, whose cells are marked by the symbols of “+” (participative), “o” (consulting) and “-” (informative); otherwise, there is no relationship addressed among them by the reviewed papers.

In the analyzed papers, the role of finance analysts was not addressed across the life-cycle service design, except for the work of Chew [18] who highlighted the importance of finance analysts whose consulting roles (“o”) were to cooperate with other design teams (e.g., market analysts and IT technicians). This cooperation was intended to “design for service strategy” (e.g., business and market models)—and “measure stakeholder needs”, “verify the measured needs”, “analyze the value propositions” and “formulate the service concept”. Moreover, Chew [18] also appreciated the participative role (“+”) of “finance analysts” required to “design for service system architecture” in terms of the monetization process linked to the business strategy. Although Iriarte et al. [42] did not discuss the role of finance analysts in the design team, they explicitly highlighted the participative involvement (“+”) of “executive officers” across departments (e.g., business managers, project managers, sales managers) to “analyze the business context” in the very first design phase. They also underlined the participative roles (“+”) of “researchers” who offered their design knowledge to facilitate their case company to “analyze the business context” and other design processes. Instead of highlighting an individual role, cooperation among design teams has also been noted as essential, as emphasized by Papazoglou et al. [64]. Specifically, marketing analysts, designers and engineers—who are responsible for manufacturing and maintenance—work participatively together with external stakeholders (e.g., customers, third-party suppliers) to verify whether or not customer needs can be fulfilled with the company capability (e.g., product-service design, production scheduling and capability, commissioning).

Table 3
New service development methods, as extracted from Appendix A.

Method group	Analysis objective	Design methods
Idea exploration	To seek design ideas through the exploration of both primary and secondary data about customer needs and wishes as well as market requirements in general.	Interview techniques: narrative interviews, in-depth interviews, contextual interviews, and open-ended interviews. Survey techniques: face-to-face survey and closed-ended email surveys. Observation techniques: ethnographic and empathic research, daily probes, contextual design, field notes and investigations, market observation and analysis, scenario observation, and laboratory visits. Secondary research: desk research, literature review, trend and experiential research, and technological studies. Focus-group techniques: brainstorming techniques, and Delphi method.
Participatory design	To allow stakeholders to have the active involvement in the co-creation design process of value proportions that ensures design solutions meet their needs and are usable.	Workshop techniques: Gender-Café debate, Generative labs, Barcamps, creative co-design workshops, experience sharing workshops, open dialogue approach, and future sessions. Participatory innovation methods: service design labs, Ideathon, Hackathon. Role-playing techniques: service role-playing, voting and mutual consensus.
Customer experience-centered methods (CX-centered methods)	To offer systematic approaches for the analysis of requirements and experiences of customers and then looking for design solutions, enhancing customer experiences at all touchpoints.	Service design visualizations: customer value constellation, extended customer experience modelling, and constellation map for PSSs. Service mapping techniques: empathy map, interaction map, actor network map, customer journey map, user experience journey visualization, organizational network map for PSSs, stakeholder motivation matrix, stakeholder system map, mind mapping, service road map of channel experiences and operational requirements. Personas and storytelling techniques: storyboards, photo-essay and photo-diary method, and persona method. Value proposition canvas, multisided value proposition canvas. Human-factors and ergonomics. Color, material and finish design (CMF design).
Idea clustering	To classify and rank unstructured data and organize them into homogeneous groups.	Affinity diagram (KJ method). Kano model. Idea ranking.
Prototyping methods	To enable design teams to convert design ideas into tangible forms that can be tested and evaluated.	Ideation: sketched images, UX/wireframe sketches, paper prototyping. Concept validation: wireframes. Refinement and usability: physical prototypes and equipment, software mock-ups, GUI design, 3D modelling.
Operations-centered methods	To design and map outbound service operations with inbound service operations.	Service operational mapping: value matrix for PSSs, navigation map for PSSs, service system navigation, service encounter and experience design, service blueprints.
Business analytics	To gain business insights and drive business planning that manages the development process of service toward sustainability.	Business model canvas. Service lifecycle management. Game theory. Contingency theory. Profit formula.
Engineering methods	To engineer the service development process toward efficiency (e.g., removal of non-valued activities during the service design) and effectiveness (e.g., usable designs that meet accurately customer requirements in first place without reworks).	Service quality model: SERVQUAL model. Statistical model: linear regression model. Improvement techniques: TRIZ (creative problem-solving techniques), Lean, benchmarking, hierarchical task analysis. Manufacturing blueprints: unified modelling language diagrams (UMLD), decision trees, 3D interactive visual platform for product-oriented configuration language, ontology web language, supply chain operational reference processes, business process model and notation, modularity principles.
Evaluation methods	To evaluate the outcome (efficiency and effectiveness) of a design process using both quantitative and qualitative manners.	Statistical validity: hypothesis testing *(analysis of variance)* on usability, *t*-test, chi-square test. Usability testing: interviews, workshops, surveys, field notes and observations, SUS questionnaire, computer system usability questionnaire, heuristic evaluation, think-aloud protocol. Ergonomics evaluation methods: task analysis. Key performance indicators (KPIs).

To this end, DIMAND has been equipped with the complete piece of information about stakeholder involvement, offering a complete guideline on how to oversee and plan "who will do what" across the life-cycle service design. Beyond the external stakeholders (e.g., customers, third parties), DIMAND encourages design practitioners to take the (direct and indirect) involvement and understanding of the internal actors (e.g., executive officers, marketers, engineers in manufacturing and maintenance and product engineering) into the design decisions, fostering value co-creation capabilities on advanced service design.

4.3. New service development methods

For the third part of knowledge representation (Fig. 1), the new service development methods must be both non-engineering (e.g., participatory design, interviews) and engineering methods (e.g., quality function deployment, statistics). This requirement shapes the way new service development methods were synthesized. In particular, this synthesis was realized by categorizing the "design methods" of the analyzed papers extracted from Appendix A. Table 3 shows the homogeneous categories of these methods and now they share mutual objectives. Specifically, when it comes to "measure stakeholder needs", Hartono [38] carried out the design methods of a "face-to-face survey" and "interview" to explore the experiences of customers (e.g., happy, satisfied) within service design. Similarly, Camussi et al. [13] captured the service ideas specified from customers through "ethnographic observations" and "narrative interviews". Although these methods are different regarding their execution techniques and usage contexts, they share mutual objectives: to seek human ideas for service design.

As a result, the bottom of the right pillar (design elements) of DIMAND (Fig. 4) integrates these new service development methods, as presented in Table 3. This integration interlinks with the life-cycle service design through the grid matrices, whose cells are marked by "A" in DIMAND; otherwise, there is no relationship addressed among them as seen by the analyzed papers. Thus, the integration realizes the relation between them (R2 in Fig. 1). Specifically, Hartono [38] replied on the method group "idea exploration" (e.g., face-to-face surveys, interviews) to "measure stakeholder needs" (e.g., the quality perception of clients about airport services); this relationship is symbolized by "A" in DIMAND. Similarly, Camussi et al. [13] also applied the same method of "idea exploration" (e.g., ethnographic observations, narrative interviews) to "measure stakeholder needs" by capturing the stories, needs and desires of customers in the healthcare system. Alternatively, Kumar and Maskara [50] applied the both method groups: "idea exploration" (e.g., ethnography, observation and interview) and "participatory design" (e.g., workshop techniques). These human-centric design methods allowed the authors to "measure stakeholder needs" regarding functional and non-functional requirements in design for healthcare software, such as technology adoption, painful areas in usability and human factors (e.g., values, beliefs, attitudes, user experience and clinician preferences).

By realizing the interconnection between the new service development methods and the life-cycle service design, one can seek what the design method can be used for, hence enabling the execution of the specific design processes. In the reverse direction, one can also answer the following inquiry: What design methods can a design process apply? For example, the design methods for 'idea clustering' (e.g., affinity diagram, Kano model) may be used by four design processes—"select the service domain", "verify the measured needs", "analyze the value propositions", and "formulate the service concept"—in the life-cycle service design, which is symbolized by "A" in DIMAND. In the reverse direction, to "analyze the business context", one may want to apply-one or more design methods of "idea exploration" (e.g., field research, desk research) and "participatory design" (e.g., workshops, Barcamps) to acquire the design output: "background knowledge for design". A design practitioner can also apply "engineering methods", such as hierarchical task analysis, to "measure stakeholder needs" in terms of user physical tasks and goals. For some advanced services related to social-technical systems (e.g., digital dashboard for decision making), other engineering methods, such as the functional resonance analysis method [66], may be required to measure the time-stamp information between cognitive workload and technical resources embedded in such advanced services.

As a result, DIMAND is not only the life-cycle service design, but it also shows how the design phases and processes can be supported and implemented by the sets of new service development methods (Table 3) that are viable and have been proven in the literature to work. This allows design practitioners and engineers to be aware of a wide range of both service- and engineering-specific methods that supports the

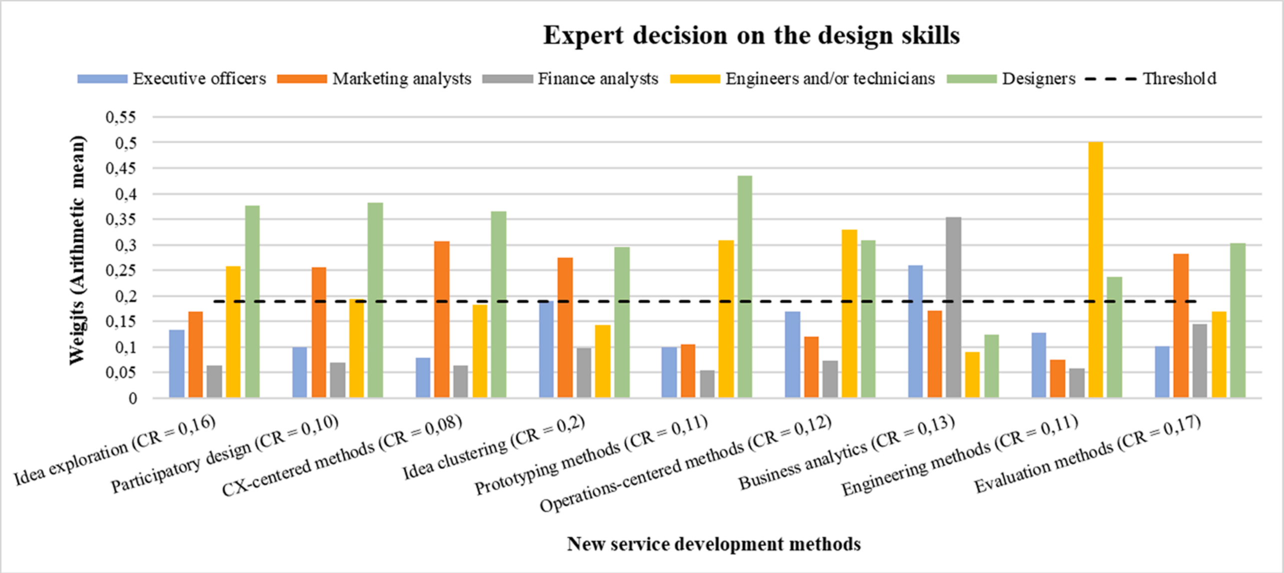


Fig. 7. Expert decision on the design skills. This result is extracted and visualized from the dataset [61], including: the expert survey, its dataset (expert responses) and the R codes for the AHP analysis. Based on the importance weights in the arithmetic mean, the expert responses are tolerably consistent in the conclusion that two or three groups of the design teams—whose importance weight values are higher than 0,19 (threshold), hence dominating that of the other groups—should master a group of new service development methods as their skill set.

transdisciplinary approach required for advanced service design.

4.4. Design skills

For the fourth part of knowledge representation (Fig. 1), design skills represent the ability of internal stakeholders (design teams), who practice new service development methods to perform design activities across the life-cycle service design. Therefore, as mentioned in Section 3.2, Nguyen, Lasa, Iriarte, Atxa, et al. [62] designed the expert survey containing skill-rating questionnaires in the form of a pairwise comparison. These pairwise questionnaires capture the importance weights of all design teams on the acquisition of the new service development methods, as design skills, from the experts (Table 1). Specifically, based on the Table 3, there are nine groups of new service development methods used to form nine corresponding skill-rating questionnaires in the form of pairwise comparison matrices (the reciprocal matrix of Equation (1)) among five groups of design teams (Fig. 6). The dataset [61] provides fully the expert survey, its dataset (expert responses) and code availability (R language) for the AHP analysis. The detailed description of the dataset [62] offers complete instructions on how to analyze the dataset in accordance with the AHP procedure.

To summarize the result, Fig. 7 visualizes the importance weights of the design teams on the need to acquire new service development methods as design skills. Because all values of consistency ratio (CR) are no more than 0,2 [54,78], the expert responses are tolerably consistent in the conclusion that two or three groups of design teams should be prioritized to master a group of new service development methods as their skill set.

According to the experts, the “designers” and “engineers and/or technicians” should be more preferred to master the skill set of “idea exploration”—which supports them in acquiring design ideas through the exploration of customer requirements and/or markets—than the other groups of design teams. Similarly, the “executive officers” and “finance analysts” are more preferred to equip the skill set of “business analytics” to be competent in gaining business insights and driving business planning that can manage the service development process towards sustainability. The same reasoning is applicable to the rest of the design teams.

As a result, the right pillar of DIMAND (Fig. 4)—which connects the internal stakeholders (design teams) with the new service development methods—also integrates these prioritized design skills, here in line with Fig. 7 whose bar values of importance weights are higher than 0,19 (threshold). This connection realizes the relation between them ($R3$ in Fig. 1). As can be seen by the “S” symbols integrated into DIMAND, this reveals the transdisciplinary design team, in which two or three job roles (design teams) should practice a specific group of service development methods; this also shows how a company should make decisions about the training priority among its design teams. By building the transdisciplinary design team, the skills and mindset from different fields (e.g., service, engineering and industrial design) can function as an accelerator for the design of advanced services to the market by combining technological design and HCD [2]. Among the design teams, except for the skill set of “business analytics” (e.g., game theory, contingency theory), “designers” are required to practice all skill sets. In line with this result, Calabretta, G. and De Lille [12] suggested a much broader role for design professionals in the company to enable the transition process towards the effective design of advanced services. In addition to designers, the roles of “engineers and/or technicians” and “marketing analysts” were also emphasized. The engineers—who may come from different departments, such as research and development, manufacturing and maintenance, and quality assurance—should not only be qualified in technical skills, including “prototyping methods”, “operations-centered methods”, and “engineering methods”. But they should also understand what customers want in both the functional (e.g., technical problems, service quality reports) and non-functional requirements (e.g., user perception, cognitive and work domain). Comprehending customer requirements can be more effective by training the skill sets of “idea exploration” (e.g., focus-group and interview techniques) and “participatory design” (e.g., service design labs and workshops) for both engineers and marketing analysts. Coreynen et al. [23] also stated that front-office staff need to master service skill sets beyond their professional skills to support in upscaling or in the successful adoption for the design of advanced services.

Table 4
Participation of 26 design practitioners and engineers in the SUS survey.

Job role	Sector	Job role	Sector
#01 Design for engineering	Consumer goods	#14 Design for UX/UI	Governmental organization
#02 Design for engineering	Equipment goods	#15 Design for UX/UI in industry	Equipment goods
#03 Design for industry	Component manufacturer	#16 Innovation management	Telco
#04 Design for product and service	Finance	#17 Innovation management, advanced product quality planning (APQP)	Component manufacturer
#05 Design for product and service	Telco	#18 Maintenance management and operations research	Equipment goods
#06 Design for product and service	Equipment goods	#19 Maintenance, quality, strategy and operations consulting	Equipment goods
#07 Design for product and service	Component manufacturer	#20 Manufacturing development for digitalization	Equipment goods
#08 Design for product and service	Innovation consultancy	#21 Manufacturing process engineering	Software development
#09 Design for service	Design consultancy	#22 Mechanical and automation design	Research center
#10 Design for service and industry	Research center	#23 Mechanical design, design for product	Innovation consultancy
#11 Design for service and industry	Innovation consultancy	#24 Mechanical design, project management	Equipment Goods
#12 Design for strategies	Household appliances	#25 Mechanics and industrial production	Consumer goods
#13 Design for strategies	Consumer goods	#26 Mechanics and industrial production	Research center

To this end, DIMAND aids practitioners in developing the internal service capability (“who needs to know what”) and makes the decision on the training priority among cross-functional design teams through these skill sets (the “S” symbols). This capability building helps the company develop and nurture the transdisciplinary design team, in which the skills and mindsets from different fields can function as an accelerator for the design of advanced services.

In summary, the final structure of DIMAND encompasses all interconnected key design elements in a single-view structure (Fig. 4) in accordance with the human-centric approach. As a result, DIMAND guides design practitioners and engineers so that they can obtain coherence in the life-cycle service design and simultaneously take the relations among the key design elements into consideration in their design decisions, making the design of advanced services more practical. Finally, we ensured the potential utility of DIMAND by quantitatively measuring its usability through SUS.

5. Usability assessment

Nguyen, Lasa and Iriarte [60], and Haber and Fargnoli [35] pointed out that design methodologies in the literature lacked evaluations of their utility. This encouraged us to overcome this limitation by evaluating DIMAND for the sake of enriching our research contribution; this validation ensured that the knowledge representation of DIMAND matched the design purpose within the domain of advanced services

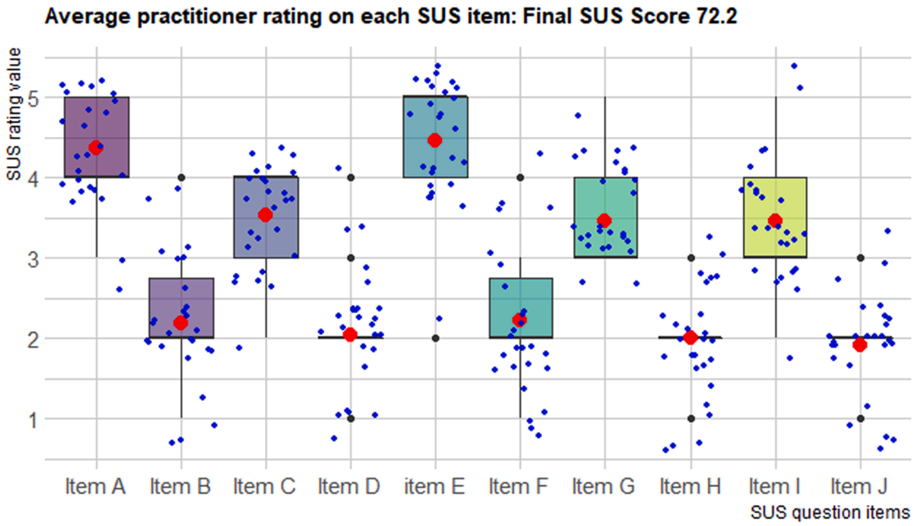


Fig. 8. Practitioner assessment of DIMAND's usability through the SUS questionnaire. Items A to J represent the corresponding SUS question items proposed by Holden [39] (e.g., "I would use DIMAND", "DIMAND was too complex for me", "DIMAND was easy to use"). The red/big dot on each boxplot (SUS question item) is the average rating value given by the 26 practitioners. The green/small dots are the practitioner individual rating values, with a small amount of random variation to their original locations as a mean to avoid overlaps among them [89]. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

[37]. Therefore, we used a simplified version of the SUS: a 10-item questionnaire measuring the usability perception applied on a 5-point Likert response options (strongly disagree to strongly agree). This SUS was improved by Holden [39] in terms of the wording from its original version proposed by Brooke [9]. SUS can robustly be used across many domains, such as engineering design [30], software engineering [94] or smart PSSs [17]; SUS is also robust with a small number of participants and is easily understood by participants with diverse disciplines [58]. These characteristics make SUS applicable for measuring the perceived usability of DIMAND from the perspectives of practitioners who bridge the gap between academic knowledge and implementation in practice.

Subsequently, based on Cohen [20], we determined the proper sample size as having a medium effect size of 0.5 and power of 80 % for the one-sample *t*-test. As a result, we recruited a total of 26 design practitioners (see Table 4) who have worked between two and more than five years as designers (e.g., user interface and user experience design (UX/UI), product and service design) and engineers (e.g., mechanics, industrial production, maintenance) to join the assessment. Table 4 shows their diverse disciplines in different industries (e.g., equipment manufacturers, consulting and research centers), ensuring the usability of DIMAND is well perceived by a wide range of design teams' profiles. Before the assessment, we ensured that these practitioners understood how DIMAND worked by communicating the same explanation presented in Section 4.

Fig. 8 presents the average rating given by these practitioners on each SUS item. The final SUS score of the DIMAND structure (Fig. 4) is 72.2 out of 100 from a practitioner perspective. Based on the adjective range of SUS scores reported by Bangor et al. [7], DIMAND's usability falls into the "excellence" rating.

By taking a detailed look at Fig. 8, the odd-ordered SUS items have the average rating values of more than 3, showing a positive usability assessment for DIMAND. Two of them, including item A ("I would use DIMAND") and item E ("The various parts of DIMAND were well integrated"), possess the higher average rating values at around 4,5 (between agree and strongly agree). This shows that the practitioners appreciated DIMAND as a multidimensional design methodology for compressing design knowledge by integrating the key design elements (Fig. 1) in a single-view structure in accordance with the human-centric approach. On the other hand, the even-ordered SUS items have average rating values around 2 (disagree), indicating the potential utility of DIMAND in practice under the central perspective of the practitioners. Specifically, the usability issues in DIMAND reflected by, for instance, item B ("DIMAND was too complex for me") and item D ("I really need help from someone to use DIMAND") were not a concern of the practitioners.

Above all, these SUS results validate that the knowledge representation of DIMAND (Fig. 4) matches the design purpose within the domain of advanced services: the (1) life-cycle service design interrelated with (2) stakeholder networks; (3) new service development methods; and (4) design skills in a single-view structure (its practice is presented in the supplementary information Appendix B).

6. Discussion and conclusion

Design for advanced services has caught the attention of industries and academics as a way to exploit new customer value propositions, hence enabling companies to create new revenue streams, competitiveness and customer satisfaction; however, doing so requires substantial efforts in an in-depth and overarching view of human actors in design [60,80]. This is because human-centered thinking allows value cocreation with customers and stakeholders and manages their expectations, opportunities and risks [49,75]. Nevertheless, the existing design methodologies for advanced services do not often address human-centered thinking; a lack of consideration of human actors could cause design problems: unexpected service behavior, user frustration and even extensive redesign work [28,48]. Moreover, the existing design methodologies have been limited to partially addressing one or some key design elements, causing confusion in practice and even leading to a service paradox [52,67]. Therefore, to make a contribution to the literature, we conceptually proposed a multidimensional design methodology called DIMAND (Fig. 4). On the opposite of existing intuitive approaches, DIMAND addresses (1) the life-cycle service design interrelated with other key design elements—(2) stakeholder networks, (3) new service development methods, (4) design skills—to orchestrate design activities in a single-view structure with the human-centric approach. We developed DIMAND through a hybrid research design (Fig. 2) that can take advantage of the body of knowledge in the literature through SLR and *meta*-analyses (Section 3.1). We also elicited 10 experts' expertise through the AHP analysis (Section 3.2) accompanied with the dataset to enhance the present research transparency [61]. Subsequently, based on the SUS (Section 5), we invited 26 design practitioners and engineers (Table 4) to evaluate the usability of DIMAND and confirm its potential utility.

In particular, the current study contributes to the literature on advanced service design in four ways. First, in response to the requests from Marilungo et al. [57] and Vasantha et al. [87], we built DIMAND to address the life-cycle service design, spanning from the *diagnose* phase to the *delivery* phase (Section 4.1). Even though life-cycle perspectives have been highlighted as being essential for advanced service design, fine-grained insights have been lacking [52]. Specifically, although Yu

[95] focused solely on measuring and analyzing customer requirements, Iriarte et al. [42] and Costa et al. [25] also paid attention to analyzing the business context and then identifying proper stakeholders. Thus, our study has addressed the call by Agher et al. [3] and Song and Sakao [81] by providing DIMAND as a systematic methodology that can cover the entire life cycle service design, starting from planning and design to product/service usage with feedback loops.

Second, responding to the work of Zheng et al. [98] and Carrera-Rivera et al. [15], we have incorporated an in-depth and overarching view of human actors (stakeholder networks) across the life-cycle service design into DIMAND (Section 4.2), fostering human-center thinking in design. We have demonstrated that DIMAND expresses the visibility of collaborative and collective opportunities for both internal and external stakeholders to co-design for advanced services across design processes. Thus, DIMAND has fulfilled the requirements posed by Richter et al. [71] and Nguyen, Lasa and Iriarte [60], embracing stakeholder involvement across the life-cycle service design.

Third, the current study has demonstrated how the life-cycle service design can be conducted with a wide range of new service development methods (Section 4.3), including both engineering and non-engineering design methods. Rather than replying only to engineering methods, we embedded the new service development methods across the life-cycle service design into DIMAND, as proposed by Jing-chen Cong et al. [21] and Nguyen, Lasa and Iriarte [60]. This has allowed for transdisciplinary design (e.g., physical ergonomics, cognitive and social factors), which is required for advanced services.

Fourth, we have responded to the call by Richter et al. [71] by integrating the design skills required for advanced service design into DIMAND (Section 4.4). This has contributed to the literature related to internal service capability ("who needs to know what") and decision making on the training priority among cross-functional design teams through skill sets (the "S" symbols), as called for by Baines et al. [5] and Ingo Oswald Karpen et al. [46]. Through design skills, DIMAND encourages the mindset of building transdisciplinary design teams that are cross-functional (e.g., design, marketing, finance, manufacturing and maintenance) and involved in the making of advanced services. This mindset fosters a business culture perspective, in addition to market focus, as called for by Fernandes et al. (2019) and Gilles and Christine [29].

Finally, in relation to the practical implications for design practitioners and engineers, DIMAND (Fig. 4) offers systematic methodical support that can enable them to obtain coherence in all life-cycle design processes by simultaneously taking other key design elements—-stakeholder networks, new service development methods and design skills—and their relations into account. This holistic approach allows for the design of advanced services that are more practical in four ways. First, DIMAND addresses the life-cycle of service design, enabling design practitioners to keep the life cycle perspective in mind, utilize process dependency and contingency planning and be aware of the feedback loops among design processes in their design decisions. This allows for holistic life-cycle planning so that extensive redesign work, unexpected service behavior and even the effect of the service paradox can be avoided. Second, DIMAND is equipped with the complete piece of information of stakeholder involvement, offering design practitioners a complete guideline on how to start overseeing and planning the stakeholders' roles across the life-cycle of service design. For external stakeholders, DIMAND helps design practitioners in understanding the partnerships among them so that they can plan how to leverage several parts of the ecosystem and not only rely on one, as proposed by Fernandes et al. [27]. DIMAND also encourages design practitioners to take the (direct and indirect) involvement of internal stakeholders into collaborative and collective design activities, working towards the development of value cocreation capabilities. Third, DIMAND instructs design practitioners how to implement design processes by using sets of new service development methods that are viable and have been proven in the literature. Thus, DIMAND allows design practitioners and engineers to be aware of a wide range of both service- and engineering-specific methods that can support a transdisciplinary approach, ranging from understanding customer requirements to prototyping methods. Fourth, DIMAND facilitates design practitioners in building up transdisciplinary design teams and training agendas for cross-functional teams by providing new service development methods. The training agenda can be prioritized for a particular job role, as illustrated by "S" in DIMAND (Fig. 4), to ensure the development of a transdisciplinary design team. As a result, DIMAND encourages design practitioners to balance the design skill sets among their cross-functional teams to develop their own internal service capabilities.

Despite the rigor of this hybrid research design, we acknowledge that some relevant research papers could have been missed during the SLR because of the selection of search terms and journal papers. The interpretation of the result was also influenced by our knowledge in the field; the substantial knowledge in this research was shaped by the body of knowledge in the literature, and the recruited experts and practitioners' experience. Finally, we acknowledge that a limitation remains the conceptual methodology of DIMAND; we alleviated this limitation by presenting Appendix B, which offers the implementation instructions of DIMAND for practice. In addition, future research should aim to overcome this limitation by field implementations of DIMAND with selected multiple company cases. This field implementation can help deploy and adapt DIMAND to fit the business context of company cases, in which internal actors cooperate with researchers to design for advanced services. Through practice learning and experience during the field implementation, DIMAND will be subject to further refinement through reflection-in-action in each design process, resulting in innovation practices for company cases in particular and lessons learned for DIMAND in general.

Research data

Data transparency and code availability can be found online in Mendeley Data: Nguyen, N. H., Lasa, G., Iriarte, I., Atxa, A.;, Unamuno, G., & Galfarsoro, G. (2022a). Expert evaluation: Datasets of skill-rating questionnaires for advanced service design through Analytical Hierarchy Process. Mendeley Data. https://doi.org/10.17632/7brkgztjdx.3.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendices. Supplementary material

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CHAPTER 6

Conclusions and future work

6. Conclusions and future work

In the final chapter, the contributions of the current thesis are summarized in relation to the research objectives presented in Figure 1. The discussion also includes validation of the fulfillment of these objectives. Finally, limitations of the research are acknowledged and future work is outlined based on these limitations.

6.1. Summary of contributions and objective validation

Chart 1 shows that there is a growing interest in prioritizing humans in design across various fields, in response to changes triggered by Industry 4.0 that have shaped human roles in the value chain. As a result, there is a substantial body of literature offering theoretical frameworks, models, implementation methodologies, and case studies in cross-disciplinary contexts.

Table 1 revealed that an emerging research stream is HCD for PSS, particularly in the case of advanced services that offer risk and revenue sharing agreements with customers over the service's lifecycle. This finding limits the present thesis to focus on HCD for PSS whose special case is advanced services that offer new value creation by the delivery of product-service performance outcomes in terms of use-based and/or result-based contracts (Baines et al., 2013; Calabrese et al., 2021).

Design for advanced services has caught the attention of industries and academics as a way to create new revenue streams, competitiveness, and customer satisfaction; however, achieving this requires a comprehensive understanding of human actors in design (Solem et al., 2021). This is because human-centred thinking is crucial for value co-creation with customers and stakeholders, as well as managing their expectations, opportunities, and risks (Korper et al., 2020; Santos et al., 2018).

Moreover, other review studies, such as Marilungo et al. (2016) and Vasantha et al. (2012), conducted a detailed analysis of various design methodologies (e.g., design for PSS, service engineering) and found that while certain design phases (e.g., planning and design) were well-defined, others (e.g., implementation, monitoring, and feedback among phases) were vaguely defined or overlooked. As a result, such design methodologies are less effective in practical use.

Therefore, the present thesis aimed to propose a new design methodology that not only focuses on HCD but also encompasses the relationships among the key design elements for advanced services. This aim is accomplished by exploring two research questions: 1) What are the key design elements that contribute to an effective HCD methodology for advanced services? (RQ1) and 2) How can these key design elements and their interrelations be integrated into a unified view structure using a human-centric approach? (RQ2). RQ1 was addressed in the first two publications in Chapters 3 and 4 while RQ2 was fulfilled in Chapter 5. The following subsections present how the research questions were addressed.

Identification of key design elements

Chapter 3 presents Figure 2 that shows the key design elements that provide valuable insights into the effective application of HCD in various settings, especially in the context of PSS whose special case is advanced services. These key design elements include the life-cycle service design, stakeholder networks, new service development methods (design practice).

First, the life-cycle service design must cover all life-cycle design phases in which design processes are defined to execute their corresponding phases: the *diagnose* and *identify* phase (planning), the *measure* and *analyze* phase (design), the *navigate* phase (implementation and monitoring), and the *delivery* phase (product/service usage). This life-cycle perspective is required to guide the design of advanced services, from initial development to the end of their life-cycle, while meeting current and future customer needs in a sustainable manner. This requirement has been called by several authors, including Cheah et al (2019), Haber & Fargnoli (2019), Leoni (2019), Mourtzis et al (2018), and Pezzotta et al (2018). Hence, the life-cycle service design is considered the first key design element that must be appropriately expressed in a design methodology for advanced services to cover the life-cycle design phases associated with design processes.

Second, the role of stakeholder networks throughout the life-cycle design phases is crucial for improving the credibility of information and promoting the sharing of transdisciplinary knowledge. Several sources, including R. Y. Chen (2016), Mazali (2018), Schulze et al. (2005), and Witschel et al. (2019), emphasize the significance of stakeholder networks in providing valuable inputs in design, which may help avoid unexpected service behavior, user frustration, and extensive redesign work (Fukuzumi et al., 2017; Kong et al., 2019). It is essential to respect and analyze the diversity in interests and expectations of stakeholders to understand the impact of stakeholder interactions and their features at different life-cycle design phases, as required by Mourtzis et al. (2018), Turetken et al. (2019), and Zhang et al. (2020).

Besides, the involvement level of stakeholders is also provided because it is specific and crucial for design in practice to decide who will do what in across the life-cycle service design, as requested by Schulze et al. (2005), van Lopik et al. (2020). These modes are depicted by three levels of stakeholder involvement: (i) an informative level, in which stakeholders only provide and receive design information; (ii) a consultative level, in which they comment on predefined design scenarios; and (iii) a participative level, in which they make influencing decisions on a design process and outcome. Therefore, to create an effective design for advanced services, a design methodology must cover the second class of key design elements: stakeholder networks that address both internal and external stakeholders and their involvement in different life-cycle design phases.

Third, new service development methods are required to carry out effective design, which is called by Jing-chen Cong et al. (2020). On the one hand, these new service development methods need to incorporate non-engineering design methods such as participatory design and interviews, which can help designers focus on human diversity to gain critical design requirements. On the other hand, some reviewed case studies relied on engineering design methods such as the Kano model and quality function deployment, which prioritize and segment customer requirements for proper design (Haber & Fargnoli, 2019; Ping et al., 2020). Accordingly, to support design activities across different life-cycle design phases, a design methodology for advanced services should incorporate these new service development methods that cover both engineering and non-engineering design methods.

Chapter 3 addressed RQ1 through the identification of the first three key design elements: life-cycle service design, stakeholder networks, and new service development methods. Compared to previous reviews (Jing-chen Cong et al., 2020; Marilungo et al., 2016; Vasantha et al., 2012) that focused on only one of these elements, the present study systematically addressed all three. This was achieved based on a strict research methodology of systematic literature review (SLR) that sufficiently covers the research topic through eight reputable search databases (e.g., SpringerLink, Emerald). As a result, a total of 265 papers were identified. After careful evaluation, 188 papers were considered irrelevant and excluded from the analysis, while 77 were deemed relevant and included in the review within the context of Industry 4.0. Out of the 77 included papers, 43 were found to contain case studies that specifically focused on HCD. This approach offered evidence with a minimal amount of subjectivity and bias based on the strict review process.

Moreover, in the review process, case studies were used as a unit of analysis to allow for in-depth exploration and refinement of concepts associated with lessons learnt. This approach differed from bibliometric reviews, such as those conducted by Victorelli et al. (2020) and Zarte et al. (2020) which often lacked detailed conceptual analysis of the studies.

Even though Chapter 3 made an in-depth review on the 43 case studies through the strict review process, none of the analyzed case studies addressed design skills while these design skills are important because they affect key performance indicators in design work. This finding is also inline with the review work of Richter et al. (2019) who stated that the existing methodologies did not fully address the design skills required for design practitioners, who are typically internal stakeholders and responsible for design activities and outcomes.

Fourth, Chapter 4 presents Table 2 that shows the identification of design skills and enables design practitioners to build a transdisciplinary design team in which each group of design methods can be handled by two or three job roles, in order of priority. This contribution is called by Spreitzer et al. (2012) who emphasized the importance of equipping company staff with the necessary skills to enable them to understand how to perform and develop their work. This is also inline with Baines et al. (2013) and Ingo Oswald Karpen et al. (2017) who stated that design skills are critical factors in achieving key performance indicators in advanced service design. Therefore, training on these essential skills can help companies improve their sustainable development. This highlights the significance of everyone involved in the creation of products and/or services, promoting a business culture that prioritizes advanced service design instead of solely market orientation, as supported by Fernandes et al. (2019) and Gilles & Christine (2016).

As a result, Chapter 4 made a significant contribution to the existing knowledge where there was a scarcity of research studies that pinpoint the specific design skills required for design teams. The present thesis delivered the contribution through a reproducible research process and associated dataset for conducting multiple-criteria decision analysis with expert purposive sampling. Purposive sampling and a chain referral approach were utilized to recruit appropriate experts for the questionnaire-based research (R.R. Hoffman et al., 2008;

Robert R. Hoffman et al., 1995). This is because the experts who possess expertise in both academic and industrial perspectives are best suited to provide answers related to design skills. Furthermore, the present study also enhanced research validity through the analytical hierarchy process (AHP) that was applied to design pairwise skills-rating questionnaires that would elicit and validate expert responses to the design skills.

To this end, the full identification of four key design elements—(i) life-cycle service design, (ii) stakeholder networks, (iii) new service development methods, and (iv) design skills—addresses RQ1: What are the key design elements of an effective HCD methodology for advanced services?. This research question was addressed by the contribution of the extensive review of 43 case studies in Chapter 3 and the expert elicitation for design skills in Chapter 4.

At this stage, the identified key design elements governed how a new multidimensional design methodology for advanced services (DIMAND) was conceptualized. The full development of DIMAND (Figure 4) addresses RQ2, which is to determine how the identified key design elements and their relations are incorporated in a single-view structure that aligns with a human-centric approach. The contributions of DIMAND in both theoretical and practical contexts were presented as follows.

Conceptualization of DIMAND

Chapter 5 presents DIMAND (Figure 4) whose development was inspired by quality function deployment (Fan et al., 2019; Horvat et al., 2017) to formulate the interrelations among the identified key design elements. On the opposite of existing design methodologies that addressed partially the key design elements, DIMAND is formulated by a hybrid research methodology to capture and combine them in a single-view structure. The strict systematic reviews and structured analysis with the affinity method were applied to identify and synthesize the commonalities, differences and patterns among 21 included design methodologies oriented to HCD for advanced services.

Moreover, based on the simplified system usability scale (D. Chang et al., 2019; Gopsill et al., 2015; Ya-feng et al., 2022), the usability of DIMAND was also assessed under the perspective of 26 recruited design practitioners and engineers across different fields. As a result, Chapter 5 presents the results of the SUS questionnaire validating the knowledge representation of DIMAND (Figure 4) that is appropriate for its intended design purpose in the domain of advanced services. This purpose includes integrating life-cycle service design, stakeholder networks, new service development methods, and design skills in a single-view structure oriented to HCD.

Hence, the present thesis addressed RQ2: How can these key design elements and their interrelations be integrated into a unified view structure using a human-centric approach?. This made both theoretical and practical contributions to the existing knowledge of advanced service design in literature.

Theoretical contributions

The current thesis provides a significant contribution to the literature on advanced service design in four key ways. First, the thesis responded to the requests made by Marilungo et al. (2016) and Vasantha et al. (2012) by developing DIMAND, a methodology that addresses the life-cycle service design. While life-cycle perspectives are considered essential for advanced service design, there has been a lack of fine-grained insights in this area, as noted by Kwon et al. (2021).

Specifically, Yu (2018) only focused on customer requirements while Iriarte et al. (2018) and Costa et al. (2018) analyzed the business context and identified the proper stakeholders. Therefore, DIMAND is a comprehensive methodology that covers the entire life-cycle service design, starting from planning and design to product/service usage with feedback loops, as suggested by Agher et al. (2021) and Song and Sakao (2017).

Second, the current thesis responded to the work of Zheng et al. (2019) and Carrera-Rivera et al. (2022) by incorporating an overarching view of human actors (stakeholder networks) into DIMAND. This approach fosters human-centred thinking in design and ensures the visibility of collaborative and collective opportunities for both internal and external stakeholders to co-design advanced services across design processes. By doing so, the thesis has fulfilled the requirements posed by Richter et al. (2019), which emphasize the importance of stakeholder involvement across the life-cycle service design.

Third, the current study demonstrated how a wide range of new service development methods, including both engineering and non-engineering design methods, can be used across the life-cycle service design. This approach allows for transdisciplinary design, which is essential for advanced services. Rather than relying solely on engineering methods, the thesis made the contribution by embedding new service development methods throughout DIMAND, as proposed by Jing-chen Cong et al. (2020).

Fourth, the thesis made the contribution by integrating the design skills required for advanced service design into DIMAND, as called for by Richter et al. (2019), Baines et al. (2013) and Ingo Oswald Karpen et al. (2017). This approach contributes to the literature related to internal service capability and decision making on training priorities among cross-functional design teams through skill sets (the “S” symbols). DIMAND encourages the building of transdisciplinary design teams that are cross-functional, including design, marketing, finance, manufacturing, and maintenance, fostering a business culture perspective in addition to market focus, as called for by Fernandes et al. (2019) and Gilles and Christine (2016).

Practical contributions

Design practitioners and engineers can benefit from the systematic and methodical support offered by DIMAND (Figure 4), which enables them to achieve coherence in all life-cycle design processes by considering key design elements: life-cycle service design, stakeholder networks, new service development methods, and design skills. This holistic approach allows for the creation of advanced services that are more practical in four ways.

First, DIMAND focuses on the life-cycle service design, enabling design practitioners to keep this perspective in mind and consider process dependency, contingency planning, and feedback loops among design processes in their decisions. This facilitates holistic life-cycle planning, which can help avoid extensive redesign work, unexpected service behavior, and the service paradox.

Second, DIMAND provides comprehensive information on stakeholder involvement, guiding design practitioners in overseeing and planning the roles of stakeholders across the life-cycle service design. For external stakeholders, DIMAND helps design practitioners understand the partnerships among them, allowing them to leverage different parts of the ecosystem instead of relying on only one. It also encourages the direct and indirect involvement of internal stakeholders in collaborative and collective design activities, promoting the development of value co-creation capabilities.

Third, DIMAND offers sets of new service development methods that have been proven in the literature, allowing design practitioners and engineers to implement design processes effectively. This supports a transdisciplinary approach, covering everything from understanding customer requirements to prototyping methods.

Fourth, DIMAND assists design practitioners in building transdisciplinary design teams and training agendas for cross-functional teams, providing new service development methods. The training agenda can be prioritized for a particular job role, ensuring the development of a transdisciplinary design team. As a result, DIMAND encourages design practitioners to balance the design skill sets among their cross-functional teams to develop their own internal service capabilities.

Research limitations

Despite the rigor, relevance, and research scope, the present thesis acknowledged certain limitations. First, Chapter 3 applied the strict protocol of SLR may have led to the exclusion of some relevant papers. In order to ensure high-quality publications, the review process was limited to peer-reviewed journal articles. Moreover, the present study recognizes that the selection of the topic, definition of search terms, and interpretation of results were influenced by our prior knowledge on the subject, which could have potentially overlooked other key design elements.

The second limitation pertains to Chapter 4, which employed a questionnaire-based research methodology, where the knowledge of experts was the primary source of information used to answer the research question on design skills. Therefore, the study's generalizability may be limited due to the expert sampling procedure. Besides, the present study utilized pre-coded (closed) skills-rating questionnaires, which did not provide the surveyed experts with other potential choices regarding design skills. For instance, design practitioners or experts may consider the role of the sales team for advanced service designs, in addition to the design team members defined in Table 2. This limitation of closed-ended questionnaires has also been acknowledged by other research studies that used questionnaire-based methodologies, such as Brigham (1975), Reeve-Brook et al. (2022).

Lastly, the present thesis acknowledges the existence of certain limitations in the development of DIMAND (Chapter 5). Other relevant design methodologies could have been overlooked during the systematic reviews and structured analysis due to the selection of search terms and journal papers. Moreover, our interpretation of the results was influenced by our prior knowledge in the field, which was shaped by the existing literature and the experiences of the recruited experts and practitioners. Additionally, the conceptual methodology of DIMAND remains a limitation of this research.

Therefore, future research should aim to overcome this limitation by field implementations of DIMAND with multiple company cases in the form of longitudinal studies. The longitudinal study allows for repeated observations of DIMAND implementation over an extended period of time. Through practice learning and experience during the field implementation, DIMAND will be subject to further refinement through reflection-in-action in each design process, resulting in innovation practices for company cases in particular and lessons learned for DIMAND in general.

6.2. Future work

In order to overcome the limitations discussed earlier, future research should involve conducting longitudinal studies with multiple companies. Hence, the thesis proposes a research plan that includes designing and implementing data collection, selecting appropriate companies, and determining the timeframe for the studies. Additionally, to support the implementation of DIMAND in the field, the thesis recommends conducting research on expert interviews and operative standardization of DIMAND.

Longitudinal case studies and data collection

The thesis reached the conceptual development of new HCD methodology for advanced services (DIMAND, Figure 4). Therefore, the next research agenda focuses on the field implementation of DIMAND in multiple company cases, following longitudinal studies.

First, the case study is a reliable source in which the application of DIMAND is explored, described, explained, tested and even refined. A case study here as an empirical research method is specifically used in situations not only where the contextual details have to be analyzed, but it is good at investigating how and why questions, particularly suitable for for theory testing and refinement (Adrodegari & Saccani, 2020; Voss et al., 2002; Williams, 2011).

The structure of a case study should include the design background and/or problem related to advanced services, the company context, the issues, and the lessons learned or patterns found that are connected to the implementation of DIMAND in field practice. Additionally, data collection derived from the case study is extensive and drawn from multiple sources, such as direct or participant observations, structured or unstructured interviews, archival records or documents, physical artifacts, and audiovisual materials (Creswell, 2012; Franz & Robey, 1984; Williams, 2011). This approach's characteristics make it a suitable and core research method for the next research agenda aimed at implementing and empirically validating DIMAND in the context of advanced service design.

Second, the field implementation of DIMAND needs to be carried out through a longitudinal case study and real-time research that focuses on how DIMAND is implemented and completed during the life-cycle service design of advanced services over time. The longitudinal case study approach allows for empirical data to be collected over time, capturing ongoing events as they unfold through direct observation, as suggested by Perks & Roberts (2013). Additionally, real-time data provides a richer understanding of change processes than historical data because the researcher is immersed in the context in which events occur, as noted by Langley (1999).

Above all, the research method of longitudinal case studies are suitable for this empirical implementation of DIMAND that requires mutual cooperation and commitment between the company cases' internal actors with the researcher to go through the life-cycle design phases of DIMAND (Figure 4), ranging from the diagnosis on company cases' context to the delivery of continuous improvement in advanced service solutions.

Case selection and implementation timeframe

According to Creswell (2012), Flyvbjerg (2006), Voss et al (2002), the research method based on a case study is often criticized. One of the most common objections to case study research is the problem of generalization, where the results of one case study cannot be generalized to another case. It should be affirmed that the goal of a case study is not to test one or more hypotheses that are then statistically and universally rejected or accepted, but to gain a theory or insight that is valid for a set of claims. Nevertheless, it is possible to generalize from a single case, but this depends on the case and the selection of the case, e.g., the logic of falsification, according to which a theory or insight that is not true in one case cannot be true in general. Therefore, when conducting case studies, it is essential to select critical cases based on the certain selection criteria.

The first criterion for selecting companies to participate in the study is their maturity in advanced service design. Specifically, the study targets companies that have little or no familiarity with advanced services. This is because established companies may become comfortable with certain practices and methods over time, making them hesitant of radical change (Y.-C. Chang et al., 2012). Additionally, the companies are included in the study if they are willing to participate and share information with the researcher due to the fact that the researcher needs to work with the companies as an external stakeholder of the stakeholder networks described by DIMAND (Figure 4).

Therefore, based on the selection criteria for case studies, this thesis proposes the implementation of DIMAND in two company cases, named Macmea and Uroper to preserve their anonymity. The first case is a large enterprise (Macmea) that specializes in machining processes, machinery design and manufacturing, and automated production systems for composite structural components. It operates in various sectors, including aerospace, railway, automotive, energy, oil and gas, and metal forming. The second case is a small-medium sized enterprise (Uroper) that provides designs and solutions for manufacturing containers using blow moulding technologies for the food and household industries. Both companies have expressed a desire for advanced services that complement their existing businesses. Thus, including both a small-medium sized enterprise and a large enterprise helped to enrich the empirical results.

The expected time frame for observing, governing, and validating the field implementation of DIMAND is between two and a half to four years, as is typical for longitudinal case studies, as suggested by previous empirical research (Iriarte et al., 2023; Legarda, 2022). This time frame allows for extensive data to be collected over time data from multiple sources, such as direct or participant observations, structured or unstructured interviews, archival records or documents, physical artifacts, field notes and audiovisual materials (Creswell, 2012; Franz & Robey, 1984; Williams, 2011). By combining and triangulating these multiple data sources, the robustness of the results can be increased, and the validity and reliability of the case study can be maximized, as suggested by (R. K. Yin, 2003).

Expert interviews

In addition to the field implementation of DIMAND, the present thesis also proposes an immediate research that is to involve experts in the field of company cases (Macmea, Uroper) to take advantage of their existing knowledge, experience and expertise through expert interviews. As suggested by DIMAND (Figure 4), the experts, as external stakeholders, can point out useful design pitfalls to designers so that potential design mistakes can be avoided and success factors such as company strengths and weaknesses and market opportunities and barriers can be aware in advance. This method of expert exploitation has also been acknowledged and commonly used in service research, including Raddats et al. (2022), Benedettini (2022), Gaiardelli et al. (2021), Naik et al. (2020), Matthyssens & Vandenbempt (2008).

Operative standardization of DIMAND

Besides, the present thesis proposes the next research effort in the comprehensive development of operative templates, forms or procedures for design practice according to DIMAND. These design supporting tools (e.g., templates, forms or procedures) may be developed in accordance with ISO standards (e.g., ISO 9001) to be compatible with the possible existing management system of company cases. This allows for gradual adoption of advanced service design, quick learning curve through standardization, and then formation of innovation design practices of DIMAND.

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