Towards Mass Individualisation:
Innovation toolkit for multi-level optimisation of open platform architecture products (OPAP)

By

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A thesis submitted in partial fulfilment of the requirements for the degree of Doctor of Philosophy in Design Engineering

September 2019
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ABSTRACT

Product design for Mass Individualisation (MI) is a new product design paradigm comprising an open hardware platform and multiple modules that are integrated with the platform. It gives freedom to end-users to integrate different modules into the platform as per their choice. To realise this approach and convert it into an industrial practice, this thesis identifies key changes in traditional product design and customisation approaches (Context, Ecosystem, Perspective, Vendor, Competition, Access), key components that need to be focused on (Design & Development, Manufacturing, Assembly, Sustainability) and technologies that need to be integrated (Data mining, AI, IoT, 3D printing, Simulation, Product realisation). The findings from an industrial questionnaire survey show that the end product from MI will be more creative and innovative with 76% of responses in agreement, and offers more individualised (more than 80% of responses in agreement) and technologically advanced products (54% of responses in agreement).

Open platform architecture products (OPAP) are the key enablers for MI. A framework for the Innovation toolkit for the end-user is developed in the second phase of research. The toolkit uses a multi-level optimisation model to identify the optimal OPAP design configuration to satisfy the exact needs of end-users. The toolkit design has been approached in four different steps: Modelling of OPAP; Modelling of evaluation measures and evaluation indices with end-user preferences; Identification of the optimal module options for every configuration; Configuration optimisation. The toolkit has been applied to three product platforms to illustrate the applicability and effectiveness of the methodology. A case study on an OPAP smartwatch finds an optimised configuration with a better customer satisfaction index, 0.830, than the initial index of 0.764. These case studies show that the developed innovation toolkit can readily be applied to this type of product development to obtain an optimised and highly individualised end product.
ACKNOWLEDGEMENTS

I would first like to thank my supervisor Prof Peter R N Childs for valuable guidance and support at different phases of my PhD. His positive, empowering and motivational comments have always inspired me to do better. His interest and enthusiasm for my work have always been motivational for me. His constructive feedback has always directed me toward achieving my research goals.

I highly appreciate valuable suggestions and contribution of my colleagues Kevin, Ji, Feng, Dongmyung, Cristobal, Inty and Tanawan. I want to thank all of my friends who kept me motivated throughout my PhD.

I am also thankful to all the survey respondents, including those participants who helped to improve the survey in the initial phase. I highly appreciate valuable responses to multiple choice questions and constructive feedback to text questions which helped to obtain many practical insights on this work. The case studies used in this paper are based on the information available in the public domain about Google ARA and Axia smart chair by Nomique. I also thank BLOCKS for their engagement in the development of the parametric validation of our case study in BLOCKS.

I also thank my thesis examiners for their insightful and constructive feedback, and comments which have helped a lot to articulate this thesis better.

None of this would have been possible without the support and blessing of my parents and family, so infinite thanks to them for all the blessing and care.
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### List of Abbreviations and Acronyms (Nomenclature)

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<td>MP</td>
<td>Mass Production</td>
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<td>MC</td>
<td>Mass Customisation</td>
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<td>MI</td>
<td>Mass Individualisation</td>
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<td>OPAP</td>
<td>Open Platform Architecture Products</td>
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<tr>
<td>OEM</td>
<td>Original Equipment Manufacturer</td>
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<td>IvT</td>
<td>Innovation Technology</td>
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<tr>
<td>IoT</td>
<td>Internet of Things</td>
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<tr>
<td>CAD</td>
<td>Computer-Aided Design</td>
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<tr>
<td>RMS</td>
<td>Reconfigurable Manufacturing Systems</td>
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<tr>
<td>CS</td>
<td>Customer Satisfaction</td>
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<tr>
<td>CRR</td>
<td>Center of Remanufacturing and Reuse</td>
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<tr>
<td>EOL</td>
<td>End-of-life</td>
</tr>
<tr>
<td>CRM</td>
<td>Customer Relationship Management</td>
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<tr>
<td>ERP</td>
<td>Enterprise Resource Planning</td>
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<td>NPD</td>
<td>New Product Development</td>
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1 INTRODUCTION

Product design is a creative process that combines design thinking with the needs of customers, the strategy requirements of companies, and the constraints of regulatory agencies to develop a product (Ma & Kremer, 2016). A typical product design comprises of following stages: problem definition, conceptual design, preliminary design, and detail design (Ma & Kremer, 2016) as well as prototyping, manufacturing or production consideration. Since approximately 70% of product cost (Appelqvist, Lehtonen, & Kokkonen, 2004) and 80% (Dowlatshahi, 1992) of product quality are determined during the design phase (Daetz, 1987; Sheldon, Perks, Jackson, Miles, & Holland, 1990; Suh, 1990), so product design is a critical part of the product development. It is a source of competitive advantage and performance driver for companies (Noble & Kumar, 2010). Improvement in product design also leads to improved customer retention (Candi, 2010).

The race to innovate products has become so intense that traditional product design and development processes cannot fulfil it. Innovation in terms of product or process is one of the key concepts to address this issue. Companies need continuous renewal to survive and prosper in an environment of dynamic user aspirations. This renewal challenge is, even more, stronger in the current market where changes in technologies, customer requirements, business strategies, and competition is far more rapid than ever (Danneels, 2002). Product innovation is identified as one of the primary means of this renewal and as an ‘engine of renewal’ (Bowen, Clark, Holloway, & Wheelwright, 1994), both in literature and in practice. Product innovation will address those needs that cannot be fulfilled by existing product design and development processes. Also, increased demand for product personalisation provides a motive for more innovative rather than just incremental products. A new product design paradigm which could serve the need of adaptability, upgradability, and sustainability, and also meets the exact requirement of the end-user has the potential to fulfil this demand. This importance of the new product design paradigm needs to be recognised both in research and practice. This thesis serves as a tool for setting the scope and importance of such a product design paradigm.
1.1 THE CONTEXT

The primary research goals of this research are directed toward understanding the product innovation using the latest practice of industrial product design with the suitable product architecture.

1.1.1 Product Design Paradigms

The concept of industrial product design has changed significantly over time, from individually crafted designs to product design for mass production (MP), followed by product design for mass customisation (MC). These changes are usually triggered either by market conditions or the consumers’ desire for the product offering. An emerging literature stream posits that inclusion of users rather than internal designers in new product creation may benefit organisations because it results in a product which effectively satisfies consumer needs. The current product life cycle from product conception, design, development, delivery, usage, service, and end of life disposal has not been able to consider customers as individuals.

The increasing concerns regarding environment, climate change, sustainability, and economic benefit from products has made product design as one of the most important topics. Up until the industrial revolution, products were designed and made by craftsmen with a localised design stretching back generations (Risatti, 2013). The concepts and processes associated with MP revolutionised the way products were designed and manufactured. Later on, technological advancement made it possible to design and manufacture products more quickly and cheaply in mass quantities. This is usually attributed to industrialist Henry Ford in the early twentieth century. His assembly-line approach to the manufacturing of the Model T motor car reduced the cost of the vehicles to such an extent that ordinary workers could afford them (Womack, Jones, & Roos, 1990). The impact on the market was revolutionary, thus on the product design and development processes. Customers’ needs evolved with time along with the needs of having newer versions of products. Many companies started delivering more product variants to satisfy the increasing demand of variations without compromising production efficiency (Berry & Pakes, 2007; Jianxin Jiao, Simpson, & Siddique, 2007). This kind of arrangement in industrial product design provided a wide range of products but often increased costs and made companies less profitable.
As society’s desire to have a variety of similar products to choose from started to change, companies introduced the concept of product design for MC by providing different variants of the same product as offering to select. The idea of MC was inspired by using more common features in production with the help of standardisation of components. MC emerged in the early 1990s with the objective of satisfying customer segments by an increased variety of products (Pine, 1993). The prevailing practice of product design for MC delivers through a configure-to-order product design paradigm, which intends to satisfy explicit customer needs and based upon legacy design. MC aims at a specific definition of products and services for customers at mass production price and efficiency (Mitchell M. Tseng & Jiao, 2001). MC enables economies of scale and satisfaction of diverse expectations concurrently (J. Jiao & Zhang, 2005). Kumar (2007) furthers the scope of MC by explaining Mass personalisation as the limiting case of MC. In Mass Personalisation, manufacturer targets a market segment of one by offering more choices.

Key enablers of MC strategy are product platform and product family design as they could provide product varieties at lower costs (Marion, Thevenot, & Simpson, 2007; Park & Simpson 2005). In product family design, a set of products share many common functionalities and components with each product satisfying unique requirements of specific customers (M. H. Meyer & Lehnerd, 1997). Sharing common components provides many advantages such as economies of scale, reduced manufacturing and service complexity, increased product variety, reduced stocks, reduced development times (Collier, 1981). Thus, product family design can provide low-cost customisation of products to an extent.

The standard components responsible for common functions in these product families are defined as the product platform (Simpson, Jiao, Siddique, & Hölttä-Otto, 2014). Other definitions of product platform include a technology applied to several products (McGrath, 1995), a platform comprises of assets such as knowledge and relationships (Robertson & Ulrich, 1998) and a group of related products (Simpson, Siddique, & Jiao, 2006). Simpson (2004) further classified these product platforms into two categories: (1) Module based (discrete), defined by sets of components clustered into interchangeable modules forming the final product, (2) Scalable, characterised with adaptation by the adding or removing product instances as per variations in design variables.
Although MC offers variants of the same product, often the constrained availability of options limits the fulfilment of the end user's needs, since variants are provided by the product manufacturers themselves with few actual changes in design. Product design for Mass Individualisation (MI) aims to address that aspiration of highly individualised end products and shortcoming of existing product customisation approaches (Koren, Hu, Gu, & Shpitalni, 2015). Individualisation refers to abilities and strategies that aim towards the design and manufacture of precisely tailored products for individual end-users. Unlike mass personalisation (Zanker, Rook, & Jannach, 2019), end product in MI is the end result of creativity from all the actors than just the manufacturer. Better and real-time connectivity between different actors and access to resources, individualisation has been seen in various industry sectors as a promising strategy that makes the market of one a reality. Design and development of this product design paradigm is challenging for many aspects which involves selection of business strategies considering multiple market actors, engineering customer needs and choice-related issues, along with engineering aspects of design, such as manufacturability, technological aspects, and design support system. Products from MI tend to disrupt existing value chains, would require to rethink and retool everything is being done internally and externally in organisations. Mass Individualisation is a nascent field of product design, and very little research has been conducted so far.

![Figure 1.1 Different product design paradigms](image)

**Figure 1.1 Different product design paradigms**

Every product design paradigm includes three important steps: Design the product, Make the product and Sell the product (Koren et al., 2015). Based on the sequence of these three steps, the end user’s engagement and role in designing the product, all product design paradigms can be summarised as Figure 1.1. Regarding customer involvement, craftsmanship, MP, MC and MI essentially envision the strategies of “design-for-customers” (via “sell”), “design-of-
customers” (via “sell”) (R. J. Jiao, 2011), “design-with-customers” (via “sell” and “design”), “design-to-customers” (via “sell” and “personalised design”), respectively.

1.1.2 Clarification on the notions of Mass Customisation, Mass Personalisation and Mass Individualisation

As mentioned in the previous section, MC provides different variants of the same product as offering to select. Thus, it enhances user experience by allowing users to control their interaction. Products are mass-produced, but the consumer is offered some limited options to customise the product or service (Fenech & Perkins, 2015). MC considers that users can put forward their needs and preferences, and can select the appropriate product which fits best to those needs and preferences. Thus, MC is user’s intelligence-driven than the manufacturer’s intelligence-driven.

On the contrary, mass personalization is based on the manufacturer’s intelligence in which the manufacturer targets a market segment by offering more choices (Kumar, 2007). As summarised by Fenech and Perkins (2015), in mass personalisation, products are mass-produced but can be modified by the manufacturers to fit user preferences identified through existing data about the users. This approach does not involve any input from the user besides allowing the use of their purchasing or profile data. For example, e-commerce website Amazon personalise the home page of users based on their search and purchase history, and further offer their customers special offers.

Linden, Smith, and York (2003) describes personalisation as a platform to tailor information to an individual user’s specific needs and preferences. Through this approach of tailoring, several improvements in products and services can be achieved. These improvements include, among others, fewer interaction efforts for a user to find the specification of services or products they are interested in, the recommendation of new relevant products or services a customer never thought of, and related sales increment (Linden et al., 2003).

Tiihonen and Felfernig (2017) summarises that the overall idea of personalisation is to tailor contents to known wishes and needs of a specific user. The related information is stored in a user model that is used to extrapolate which items, such as products, services, or units of information, should be shown to a user. This extrapolation can be achieved in many different
ways. One of the contemporary and widely used personalisation approaches is the use of artificial intelligence that supports the identification of items that should be shown to a user, also known as recommendation technologies (Zanker et al., 2019). Zanker et al. (2019) describes this in his paper on online personalisation, where a system makes assumptions on an individual’s needs and preferences, in order to tailor content and interaction, so as to provide the most relevant user service and experience. Similarly, Larsen and Tutterow (1999) describes mass personalisation as the process of providing relevant content based on individual user preferences or behaviour.

Haiyan 2006 presents a framework for classifying approaches to personalization that delineates fundamental personalisation assumptions in the literature and relates them to strategies for developing personalization systems. Kumar (2007) explains mass personalisation as the limiting case of MC.

Although MC and mass personalisation offers variants of the same product, often the constrained availability of options limits the fulfilment of the end user's needs, since variants are provided by the product manufacturers themselves with few actual changes in design. This can be addressed by product design for MI. Unlike MC and mass personalisation, the end product in MI is the result of active participation from all the actors, including end-users and manufacturers. The approach of MI is the key product design theme for this thesis. MC is used to illustrate the development of product design for MI in different chapters of this thesis. However, the concept of mass personalisation is beyond the scope of this thesis and a matter of separate research.

1.1.3 The Problem

The central aim of this thesis is to understand product design innovation with the latest practice of industrial product design and industrial innovation. The fulfilment of this aim is achieved by addressing the following key research questions:

1. How does a change in Product Design approach help to nurture and accelerate creativity and innovation?

2. What are the key enablers of product design for Mass Individualisation to obtain a highly individualised, technologically advanced, innovative and sustainable end products?
3. How can end products be optimised in product design for Mass Individualisation considering the active role of the end-user, module supplier and platform manufacturers?

4. How can the MI be implemented in the market and its benefits be delivered to end users?

1.1.4 The Solution

Nonaka and Takeuchi (1995) developed a knowledge conversion model which describes four stages through which knowledge is acquired, shared, developed, and integrated to create new insights, transferring between tacit and explicit forms. These stages are (1) Socialisation, creating knowledge through social interaction; (2) Externalisation, articulation, and coding of knowledge into a tangible format; (3) Combination, combination of discrete pieces of knowledge to create new knowledge; and (4) Internalisation, to make new knowledge embedded in the minds of knower. Following the basics from this knowledge conversion model, different approaches to traditional product customisation and innovation will be explored to understand and investigate product design innovation.

As the initial study identifies product design for MI as the potential approach for product design innovation, this will be further explored. MI has the potential to provide an incentive for networked creativity and innovation in product design. To address the second key research question, different key areas and components as enablers of product design for MI will be identified with literature exploration of existing product design and customisation approaches. The role of networked innovation in terms of iterative feedback from all the actors will be investigated to realise this new product design paradigm. The output of this phase of research will be validated with an industrial questionnaire. Insights from this questionnaire will be used to strengthen the concepts identified.

Qualitative analysis with multiple case studies has been carried out to strengthen knowledge of various aspects of the new approach. To obtain a highly individualised and optimised end product, an innovation toolkit has been developed for the end-user. The research documented in this thesis offers a broad understanding of MI with a basis for further development in terms of design research and practice.
### 1.2 Innovation Aspect

Innovation is the key to maintain a competitive advantage in a market and fulfil today's customers’ increased aspirations. Garcia and Calantone (2002) mentioned that innovation comprises “the technological development of an invention combined with the market introduction of that invention to end-users through adoption and diffusion.” This thesis explores product design innovation considering the theme of MI in the centre. The definition of product design innovation encompasses definitions of product innovation and process innovation.

A product innovation is the development of a novel or significantly improved good or service over the existing one in terms of its characteristics or intended uses (OECD, 2011). Product innovations incorporate both new products and new uses of existing products. This also includes considerable improvements in extant of the fulfilment of user needs, technical specifications, product architecture, components, materials, end-user accessibility, and other functional attributes. A process innovation is the introduction of a new or significantly improved delivery strategy (OECD, 2011). This incorporates significant improvement in terms of techniques, design support system or toolkit for end-user. Process innovations aim to ease the process of product selection, to decrease the cost of production, to increase quality, and to fasten the delivery of individualised products.

The strengthening of innovation requires the participation of all actors and access to the growing global knowledge. There is growing interest in the literature too on the subject of effective processes for innovation and regarding how to create effective networks to encourage innovation (Autio & Thomas, 2014; Birkinshaw, Bessant, & Delbridge, 2007; Gawer & Cusumano, 2014; Rohrbeck, Hölzle, & Gemünden, 2009). Earlier research on R&D collaborations put cost saving in the primary focus (Williamson, 1975), but recent research focuses more on how these collaborations can enhance innovation and finally the value creation for the organisation (Gassmann, Enkel, & Chesbrough, 2010). Innovation within an organisation has been studied and well documented by many scholars. The influence of organisational cultures on the knowledge creation process and fostering of innovation was researched by Auernhammer and Hall (2014). They investigated the links between knowledge, innovation, and performance with the introduction of ‘Freiraum’ which means
free space emphasising on human creativity, innovation, and encouragement of knowledge redundancy through changed perspectives.

User-driven innovation has been extensively utilised and mentioned in the literature and industries, i.e., elevator industries (Boutellier, Gassmann, & Von Zedtwitz, 2008; Herstatt & Von Hippel, 1992). The cross-connection between different actors involved in the design process requires new creative and innovative approaches. It requires changes in the way traditional product design and innovation are approached. These new products can apply algorithms and analytics to use data to significantly improve output, efficiency, and utilisation. Across many industrial sectors, the end product will be far more efficient, effective, reliable, reusable and more fully utilized, with conservation of scarce natural resources such as energy, water, and raw materials. The end product in product design for MI is the end result of creativity and innovation of various actors, from platform producers to module option suppliers to end-users. This kind of networking provides sufficient incentive for networked innovation which has been explored considering Innovation 4.0 in the centre.

Compared with traditional product customisation approaches, the variation of configuration and parameters is too high in product design for MI. To capture innovation from these variations, this work proposes a framework for an innovation toolkit which would be used to obtain a highly innovative and individualised end products. An innovation toolkit describes a design environment which enables and empowers actors to formulate their requirements iteratively and transfer these into a producible solution by an iterative process with continuous live networked support from other actors in the MI ecosystem. Innovation 4.0 places emphasis on the technological integration of different actors. An important approach for this work is the technological integration via networked innovation toolkit.

Figure 1.2 summarises need, problem and solution aspects of industrial product design innovation. As briefly mentioned in the previous paragraphs, a collaboration between various actors, individualisation of products, user-driven innovation, technological innovation, internationalisation of innovation process and sustainable innovation are key topics which have immense potential to encourage product design innovation.

Need and problem aspects of industrial product design innovation have been addressed well in the literature (Garcia & Calantone, 2002). This research targets on the solution aspects.
With the literature review on industrial product design innovation, three important solution spaces are identified: sources of innovation, means and who offers, as illustrated in Figure 1.2. This research combines all these key solutions of innovation along with the latest practise of industrial product design to obtain most individualised and most innovative end products.
**Need**

**Problems**

**Solutions**

**Product Design Innovation Areas**
- Individualization of customer needs
- Internationalization of innovation processes
- Collaboration with other companies, institutes and academia
- Innovation and knowledge management
- Faster to market, shorter project lifecycles

**Areas of Innovation**
- Strategy & Methods
- Technology & Products
- Processes & Organization
- Society, Communication & Culture

**Obstacles to Innovation**
- Networking between actors
- Limited access to resources
- Culture insufficiency
- Misaligned processes
- Insufficient IT structure
- Insufficient Information

**Sources of Innovation**
- Different actors of product design and development process (Platform producers, module options suppliers)
- End-users
- Design support systems
- R & D internally
- Academics facilities
- Innovation intermediaries

**Means**
- Internet as an information source
- Internet as intermediaries to knowledge carriers
- Platform providers that enable access to knowledge carriers
- Networking events and conferences
- Academic and industrial hackathons

**Who Offers**
- End-users
- Module option suppliers
- Platform producers
- Industry experts
- Academic/institutional experts
- Science

*Figure 1.2 Taxonomy of product design innovation*
1.3 STRUCTURE OF THE THESIS

The main contribution of this thesis is understanding product design innovation using MI with OPAP. This research is first of its kind in addressing the demand of market to one with the help of product design for MI with OPAP; thus the thesis starts with the introduction of various product design paradigms, followed by the key problems and solutions this work aims to address. MC is a growing interest area in academia as well as in industries and well established. This research further this interest area with the introduction of MI with OPAP as a key enabler. This thesis is positioned to connect established literature on customisation to innovative propositions for individualisation. The thesis also provides a framework for an innovation toolkit which opens a new frontier in user-centric customisation and provides ample opportunity to explore and build on this concept. Considering the position of this thesis in established product design paradigms and to introduce new concepts, the thesis has been divided into six chapters, following the traditional structure of an academic thesis.

These six chapters cover different phases of the research. Figure 1.3 illustrates the structure of the thesis summarising three phases of the research and associated chapters in the thesis. After establishing the connection between existing literature and the proposed research themes, the first phase of the research aims to identify key areas and components need to be focused to realise and implement product design by MI in the literature and in the market. In the second phase, a questionnaire is designed to get practical feedback for industrial implication on the proposed approach. The final phase of research deals with the development of an innovation toolkit with multi-level optimisation model to identify optimal OPAP for end-users, followed by case study validation.

Three phases of this research have been divided into respective literature reviews, research methodology, and finding and discussion. These three parts of every phase have been included in combined form in different sections of chapter 2 (literature review), chapter 3 (research methodology) and chapter 4 (finding and discussion). Chapter 5 is an extension to chapter 4 (finding and discussion) and is dedicated to phase 3 of the research as it summarises the case studies, used to demonstrate the effectiveness of innovation toolkit developed in phase 3.
Summary of various chapters is provided in the following paragraphs.

Chapter 1 is an introductory chapter which sets the context of this research along with a summary of different industrial product design paradigms and a brief explanation of the role of innovation in product design. This chapter also describes research questions this thesis aims to address.

Chapter 2 describes all the key concepts along with associated literature and their position in existing literature. With the help of schematics of introduced concepts and comparison tables, this chapter establishes a clear connection between existing and proposed concepts. The ecosystem for MI has been developed, and the roles of different actors have been explained.

Chapter 3 presents the research methodology adopted in this work. This work used the mixed method research with qualitative exploration and quantitative analysis for validation of developed frameworks for MI ecosystems and innovation toolkit. Systematic literature analysis is selected to identify the key areas for realisation and implementation of MI with OPAP in the market. Industrial questionnaire survey and industrial interview are designed to obtain market insights and to build on further.

Chapter 4 highlights and discusses various research findings along with analysis. This chapter identifies key areas which need to be focused on to realise this approach and convert it into an industrial practice by an explorative study of existing product design and customisation approaches. The findings of industrial questionnaire show that the end product from product design for Mass Individualisation will be more creative and innovative, and offers more individualised and technologically advanced products. This chapter also explains the developed framework for the Innovation toolkit for the end-user. The innovation toolkit uses a multi-level optimisation model to identify the optimal design configuration for OPAP to satisfy the exact needs of the end-users. The innovation toolkit is applied to two product platforms to illustrate the applicability of the proposed innovation toolkit. These case studies show that the developed innovation toolkit for Design for MI with OPAP will help end user to obtain optimised and highly individualised end product.

The following chapter uses a case study for the parametric validation of developed innovation toolkit, with insights developed from industrial engagement. This case study has been
investigated on the parametric level to illustrate the effectiveness of the innovation toolkit on the existing market products.

Chapter 6 summarises the conclusion of this research along with direction for further research. As this research on MI is first of its kind in addressing the need of the market to one with the help of OPAP, it will open new frontiers and basis for new development in existing product design and customisation approaches. This work will also contribute in terms of academic advances across and within disciplines, including significant advances in understanding, methods, theory, and application related to product design for MI.

**Figure 1.3 Thesis Structure**
2 STATE OF THE ART

The thesis outlines a nascent field of product innovation, which will become significantly more relevant in the near future. In the last few years, a demand for renewed product personalisation has been observed in some markets to satisfy the exact need of the customers. As opposed to customisation, which emphasises the satisfaction of the explicit needs of a defined market segment, individualisation aims at satisfying the specific needs of a customer. This kind of multidirectional participation from all actors also provides an incentive for networked innovation. Since this research is the development on the existing approach of user-centric product design and recent practice of industrial innovation, Open Innovation, the following sections explain and relate different key concepts associate with this research with literature.

2.1 INNOVATION 4.0

The proposed research aims to investigate the role of innovation in the product design process with the theme of networked innovation. The basis for the approach to networked innovation is the industrial practice of open innovation. Open innovation is the application of purposive inflows and outflows of knowledge to accelerate innovation (Chesbrough, 2006). A more refined definition of open innovation is given by Chesbrough and Bogers (2014), “Open innovation is a distributed innovation process based on purposively managed knowledge flows across organizational boundaries, using pecuniary and non-pecuniary mechanisms in line with the organization’s business model.” Access to resources and internationalisation of research and development activities made open innovation more feasible and achievable.

Collins (2015) developed new tools for the management of the technology and the interface between innovator and organisation. An organisation can be seen as an entity, a fluid process or combination of both (Auernhammer, 2012). However, large vertical integrated organisations are joining a more vibrant mix of organisational forms (Langlois, 2003). Detailed empirical studies of innovation processes with different kinds of literature across different disciplines identify that firms have always sourced from outside. In the late 19th century, Edison’s laboratory displayed characteristics which were showing an open approach to
innovation (Dahlander & Gann, 2010). Literature shows that journey from closed to open innovation involves four main dimensions including inter-organisation networks, organisational structures, evaluation processes, and knowledge management systems (Chiaroni, Chiesa, & Frattini, 2011). SMEs often face challenges in terms of innovation, but they can overcome the ‘liability of smallness’ by opening up their innovation process (Gassmann & Keupp, 2007; Van de Vrande, Vanhaverbeke, & Gassmann, 2010).

Thus, open innovation plays a significant role in intensifying innovation process for any organisation. Acquiring innovations from external actors requires finding the external sources of innovation and then bringing those innovations into the ecosystem. Open innovation has developed from a research interest of a few to a mainstream research practise in recent time. It has mainly been studied in terms of different open innovation modes such as R&D outsourcing and licensing, external cooperation and open innovation performance (Abulrub & Lee, 2012). In another research paper, West and Bogers (2013) suggested a four-phase model in which a linear process of obtaining (searching, enabling, filtering, and acquiring), integrating, and commercializing external innovations is combined with interaction (Feedback and reciprocal) between the firm and its collaborators. Gassmann and Enkel (2004) mentioned three core processes in opening up the innovation process: outside-in, inside-out and coupled. The Outside-in open innovation involves taking in external inputs and contributors through acquiring (Dahlander & Gann, 2010), obtaining, integrating and commercialising (West & Bogers, 2013), scouting, licensing IP, university research programs, funding startup companies, collaborating with intermediaries, suppliers and customers, and utilizing nondisclosure agreements (Chesbrough, 2006; Chesbrough & Bogers, 2014). The Inside-out open innovation involves revealing, donating or out-licensing IP and technology, spin-outs, corporate venture capital, alliances, incubators and joint ventures (Chesbrough, 2006). The Coupled mechanisms involve flows of knowledge within partners across their organisational boundaries through joint strategic alliances, joint ventures, networks, ecosystems, invention and commercialization activities (Bogers, 2011; Bogers, Bekkers, & Granstrand, 2012).

West, Salter, Vanhaverbeke, and Chesbrough (2014) identified three fundamental connections responsible for the acceptance of the idea of open innovation among managers and scholars: 1. Sources of innovative ideas often come from outside the firm; 2. Open
innovation builds on the profit comes from the innovation; and 3. An emerging interest in the role of business models. The advantages and disadvantages of different forms of openness in any firms have also been investigated in recent research on open innovation. However, the literature lacks in any holistic model of open innovation which could tell about determinants for industry type and also the limits of opening up the innovation. Dahlander and Gann (2010) studied the influence of this openness on a firm’s ability to innovate and appropriate benefits of innovation. However, this kind of engagement between internal and external actors for the innovation process requires multi-directional management and strategic integration. The current practice of open innovation faces two key challenges: firstly, a significantly increasing complexity of the innovation, and secondly, concomitantly, rising demands on innovation management. The latest practice of Innovation 4.0 addresses this complexity in open innovation as explained in the previous section. This has to be investigated with the latest practice of product design.

In product design for MI, the final product is the end result of the creativity of various actors. This approach provides considerable incentive for the role of innovation in MI. The future practice of Innovation 4.0, based on the strategy of “open innovation” first suggested by Henry Chesbrough (Chesbrough, 2003), is the best suitable innovation practice for MI. Innovation 4.0 focuses on the strategic and technological integration of various aspects of innovation (Garn & Posselt, 2014), focusing more on inclusive innovation rather than open innovation. It places the emphasis on the networking of all the areas of innovation, i.e., strategy and methods, technology and products, processes and organization, society, communication, and culture (Jeschke, 2015). Connectivity becomes the central feature in Innovation 4.0. Everybody and everything needs to be networked. By linking all the steps in the value chain, a world of possibilities opens for companies and other actors. Technological and social innovations are closer than ever. Interactive models that are interconnected with institutions and individuals which develop, test and distribute new practices and artefacts via interactive processes need to be developed.

Strategic integration requires collaboration across the value chain, all actors, markets, funding sources, and regions. This includes the increasing importance of strategies such as individualised products, first to market. Strategies such as intellectual property rights, development of the required business models, setting prices for the final products need to be
more focused. Technological integration is very crucial considering the complexity of networks between different actors. New products with new functions, arise from new technologies need to be connected. Bioinformatics is one of the examples which can be benefitted from this kind of technological integration.

This new approach will address and solve some of the challenges faced by the world today, such as diminishing natural resources, energy efficiency, demographic change. Although the Importance of Innovation 4.0 has been identified by many institutions, not much academic research has been conducted in this area. Figure 2.1 shows the evolution of industrial innovation.

![Figure 2.1 Evolution of industrial innovation](image)

**2.2 PRODUCT CUSTOMISATION**

This section captures many of the recent advances in product customisation and encompasses a broad scope of various customisation approaches. Customisation aims at reducing manufacturing efforts while providing large product variety to fulfil customer requirements in a better way. Traditionally, most products are designed by professionals working for the underlying firms in design teams because those people “have acquired skills and capabilities that allow them to perform most design tasks more effectively and at a higher level of quality” (Ulrich, 2007). However, product design paradigms have changed significantly over time, led by technological advancement. Innovation Technologies (IvT) (Dodgson et al., 2005) have facilitated new strategies for product design and development. These strategies helped in customised products with increase product variety, decreased cost and faster time to market. New technologies have democratized the tools for both invention and production
(Anderson, 2012). Anyone with an idea can use advanced and accessible technology and turn it into a product. In practice, it is not that straightforward, as different products require different combinations of strategies, design, and manufacturing.

The idea of product individualisation evolved from the mass customisation (MC) strategy. MC is a production strategy focused on the broad provision of personalized products and services, through modularized product/service design, flexible processes, and integration between supply chain members (Pine, 1993, Fogliatto et al., 2012). As Piller (2007) mentioned, since Pine (1993)’s initial research on MC which gave MC the practical wheels, not a month goes by without a significant mass customization initiative by an established organisation. Tien (2006) represented the stage where customers may influence the design and manufacture of customized goods as the order penetration or decoupling point (DP). This may take place at five points across the supply and demand chain: customer (mass production), retailer (minor customization), assembler (partial MC), manufacturer (MC), and supplier (real-time MC), thus provides different levels of customization. Fogliatto, Da Silveira, and Borenstein (2012) investigated various areas of MC research including economics, success factors, enablers, and customer–manufacturer interactions of MC which is summarised in Table 2.1.

Table 2.1 Various areas of MC research

<table>
<thead>
<tr>
<th>MC Economics</th>
<th>MC success factors</th>
<th>MC Enablers</th>
<th>MC Customer-manufacturer interactions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Producer’s side (Piller, 2004): premium price for customised products and economics of integration in terms of access to market information, customer loyalty.</td>
<td>Customer demand; Markets; Value chain: effect of modularity on supply chain (Mikkola &amp; Larsen, 2004; Ro, Liker, &amp; Fixson, 2007; Salvador, Rungtusanatham, &amp; Forza, 2004), and implementation of MC across the value</td>
<td>Design-postponement: different stages where customers can contribute (Tien, 2006); Design-product platforms: optimisation for product family design (Huang, Li, Lau, &amp; Chen, 2007); Supply chain coordination: trade-off between cost and variety (Demirli &amp; Yimer, 2008; Yao &amp; Liu, 2009); Manufacturing and Information technologies: a</td>
<td>Building the product catalogue, Configuring customer orders, Transferring orders to manufacturing, Manufacturing customized orders (Da Silveira, Borenstein, &amp; Fogliatto, 2001).</td>
</tr>
<tr>
<td>Customer’s side (Merle, Chandon, &amp; Roux, 2008):</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Extrinsic value drivers include utilitarian, individualism, self-expression, intrinsic value drivers include hedonic, pride.

| chain (Huang, Zhang, & Lo, 2007); Technology; Customisable offer; Knowledge. | database of customer’ demand, integration of information flows (Dietrich, Kirn, & Sugumaran, 2007); Order elicitation: decision support system for collaboration, attribute preferences options. |

MC requires increased flexibility and reduced cycle time in product design and development. Platforming, product families and module product architecture are a few of the concepts introduced and explored widely under the circumstance of mass customisation (Ulrich, 2003). Platforming, in literature, has been described as a way to increase reuse of components and commonality within them. One of the early definitions of product platforms is to provide the market with a product variety efficiently (M. H. Meyer & Lehnerd, 1997). As briefly mentioned in the previous chapter, a typical product family comprises of a set of products sharing common components. On one side, a product family provides low-cost products, but on the other side, commonality causes lack of product distinctiveness (Robertson & Ulrich, 1998). Sharing more components leads to increased difficulty in differentiation between product variants in the market (Miller, 1999). This also causes reduced product performance, resulting in the loss of the market share (Lutz & Farnham, 1998).

Modularisation (Gershenson, Prasad, & Zhang, 2010) has also been seen as one of the feasible approaches for product customisation, but different products require different combinations of modularity and scaling to achieve required customisation while remaining cost-effective and competitive. During product modularisation, the degree of modularity can be adjusted as per type of product and the company’s strategy. The right amount of modularity yields many types of benefits for organisations. The modularity of a product can be characterised by a set of five attributes: commonality, function binding, combinability, interface standardisation, and loose coupling of components.

Recent studies have also investigated other means of achieving the customisation target. Deradjat and Minshall (2017) developed a framework for the implementation of rapid manufacturing for MC. (Shukla, Todorov, & Kapletia, 2018) investigated different barriers
inhibiting implementation of additive manufacturing for MC. Some of the barriers are limited size of certain products, slow speed of printing, cost of materials, cost of additive manufacturing printers and lack of multi-material printing. Addressing these barriers in future research would pave the way to utilise additive manufacturing for product customisation.

Customisation strategies often face difficulties in the implementation as many companies still have a single product mindset and overcoming the management inertia to change that mindset need time and resources. The increasing use of various IT platforms, web-based configurators, rapid prototyping and manufacturing processes, and implementation of user-oriented design support systems opened up various new opportunities.

2.3 EXISTING RESEARCH ON PRODUCT INDIVIDUALISATION

The driving force behind product individualisation is the positioning of customers/end-users at the centre of value creation and involving them into the product development phase. It is usually a very costly matter for firms to understand the inherent and exact need of users. Acquiring exact need is very a complex process, and conventional market research techniques acquire only the visible needs. Technological progress, increasing expectations, globalisation, and demographic changes lead to more diversified individual needs and concurrently, heterogeneous markets. User co-creation and user innovation address these challenges in the most favourable way. This also leads to the idea of product individualisation along with an active and direct role of the end-users in the product design and development processes.

The user has started to contribute in the design process in parallel to the professional design teams. Specific users are able and motivated enough to innovate and are willing to share their ideas with firms is not new and has been documented extensively (Von Hippel, 2005). User design can empower firms by improving time to market, reducing new product development costs, and, above all, by producing innovative products that are better at meeting consumer needs (Hoyer, Rajesh, Matilda, Manfred, & Siddharth, 2010; Lilien, Morrison, Searls, Sonnack, & Hippel, 2002; Ogawa & Piller, 2006). This empowerment varies as per firm type and extent of user participation. The extent of participation also affects consumer preferences at the point of purchase.
Von Hippel (2005) argued that one of the major promises of user design is to generate objectively better products. Literature has also argued that consumers may more willingly purchase products labelled as designed by users versus company designers (Schreier, Fuchs, & Dahl, 2012). Fuchs, Emanuela, Martin, and Darren (2013) highlighted the nuanced nature of user design and pointed out the need for additional understanding and careful consideration during customising consumer-based strategies. Ninan and Siddique (2006) proposed to use configuration tools to optimize and assess the feasibility of customer choices. By considering customers as both individuals and as an integral part of the design process, implicit characteristics such as personal taste, traits, innate needs, and experience become essential integral parts of product design (M. M. Tseng, Jiao, & Wang, 2010). It also helps in the inclusion of other intangible aspects such as cultural background, personal taste and likings, aesthetics preferences.

The postponement has been seen as one of the key strategies for companies to achieve product individualisation (Cannas, Pero, Rossi, & Gosling, 2018). The idea of postponement is associated with the customer order decoupling point (CODP) positioning. This allows companies to delay some supply chain activities until the customer order arrives, which results in increasing product individualisation while maintaining efficiency. Different stages of CODP can be utilised to obtain individualised end product as per change in customer’s requirements. Although this concept has been studied in many pieces of literature but it needs further investigation which includes possible levels of individualisation achievable from different configurations.

However, recent changes in user aspirations and inclination towards more individualised product offering has motivated innovators and product designers to approach a new paradigm. Customer co-creation and design of human–product interactions play a major role in the product personalisation with active customer participation (M. M. Tseng et al., 2010). The evolving nature of products is also disrupting supply and demand chains, forcing organisations to reconsider and reconfigure almost everything they do traditionally. These new types of products influence the industry structure and the nature of competition, providing companies with new competitive opportunities. They are restructuring industry boundaries and creating entirely new industries. Most of the product customisation approaches target to provide a variety of products to customers, but the perception of choice
and the joy or burden of configuration experienced by them are not well understood (W. Chen, Hoyle, & Wassenaar, 2012). There are few studies which address customer perceptions and behavioural economies for product customisation (Camerer, Loewenstein, & Rabin, 2011; Koop & Johnson, 2012).

The continuously increased aspiration level of customers and the growing saturation of the markets are the main drivers for the development of customer individualised products (Holle & Lindemann, 2015). This requires the changeability of product functions and users’ involvement in product design and implementation. These products raise a new set of a strategic decisions related to how value is created and captured, how the large amount of new and sensitive data they generate is utilized and managed, how the relationship with conventional business partners such as suppliers are redefined, and what role organisation should play as industry boundaries are expanded (Porter & Heppelmann, 2014). The net effect of these products on industry structure will vary across industries, but different perspective can be categorised. Kumar (2007) has documented the strategic transformation from mass customisation to mass personalization. Product individualisation requires more effective customers’ decision-making processes while putting forward user preferences, to develop better fulfilment capabilities.

![Figure 2.2 Transformation of manufacturing approaches (Koren, 2010)](Appendix B)
Figure 2.2 shows the transition of manufacturing in the last 100 years. The volume of each product variant is decreasing from MP to MI. At the same time, product variety is increasing, showing the demand for more individualised products. It tends to reach a situation of the market to one. Only the open platform type product architecture can address this demand and will be able to realise this paradigm shift. Initial research on this paradigm shift has been carried out by Koren et al. (2015), but to realise this approach and to convert it into industrial practice much more research need to be undertaken.

2.4 PRODUCT DESIGN FOR MASS INDIVIDUALISATION

In the last few years, a demand for renewed product personalisation to satisfy the exact need of the customers has been observed in the market. Koren et al. (2015) have named this concept ‘Mass Individualisation (MI)’, a new paradigm for industrial product design. Product design for MI is based on open platform architecture products (OPAP) that comprises of an open hardware platform, mass-produced by large manufacturers and multiple independent modules invented and produced by other smaller companies (R. K. Sikhwal & P. R. N. Childs, 2017b). With the help of an interactive design program, the open hardware platform is integrated with different modules as per end user needs. Thus the end product, which fits the exact requirements of the customer, is highly individualised (R. K. Sikhwal & P. R. N. Childs, 2017b). This paradigm is named ‘Mass-Individualisation’ as a large mass of products is produced, but each one is tailored to the needs of the individual buyer (Koren et al., 2015).

2.4.1 MI Ecosystem

The design is approached through the formulation of a product ecosystem considering platform producers, third party module vendors, and end-users. The prevailing practice of individualisation is to distinguish and identify the specific needs of the customer with their full and active involvement. Zhou, Xu, and Jiao (2011) defined product ecosystem as a dynamic unit that consists of interdependent products and users, functioning together with its surrounding ambience, as well as their interactive relations and business processes. Based on this definition, for MI, a network of different involved actors can be specified as a product ecosystem where the customer can interact with the product with the support of technical
and business system. Figure 2.3 illustrates the simplified version of the Ecosystem for MI. In the developed framework, it is envisaged that large manufacturers will provide the platform of the product along with interfaces for adding modules. These interfaces/modules can be satisfied by different module options.

![MI Ecosystem](image)

*Figure 2.3 MI Ecosystem (Sikhwal and Childs 2017)*

In terms of design, MI mainly discerns from mass customisation in three areas: MI expands the design space, MI embraces intangible customer experience, and MI enhances creativity and innovation through the democratisation of the product design process. The most significant extension of individualisation can be directly linked to the integration of experience not only in use but also in purchasing, order processing, inventing and producing components/modules, delivery, upgradation, maintenance, resale and being a producer. MI combines user-centric design with networked innovation (Ravi K; Sikhwal & Peter R N Childs, 2017). By linking all steps in the value chain, a world of possibilities opens for end-users and other actors. Also, this approach targets to translate good ideas into innovative products and services quickly.

In MI, the active and direct participation of the end-user results in the end product. The product offering depends on the innovation and creativity of many third party module
vendors that invent and manufacture modules. By this individualisation of end-users’ needs, inherent characteristics such as individual taste, choice, and experience become an essential integral part of product design and development. This industrial product design paradigm has the potential to offer many new jobs as module options manufacturers. The purchase intention and willingness of end-users to buy products will also improve with MI (R. K. Sikhwal & P. R. N. Childs, 2017b). This approach would also provide an incentive for responsible consumption of products as the end-users will owe something which exactly fulfils their requirements, an adaptable product which they can upgrade as per change in need. More actors in design and development would lead to more innovative and useful products. Large original equipment manufacturers (OEM) will provide the main platform of the product and interfaces for adding modules. Limited numbers of specific modules will also be provided by the OEM for some very specific functions of the end product. Smaller companies will invent and produce modules for the end users to use and to integrate in the platform. Thus the basis of competition shifts from discrete products to modules and product systems consisting of interfaced modules or module systems on product platform. Despite the benefits MI would deliver, it is still at the early stage with limited literature.

End products from MI offer exponentially expanding opportunities for new and innovative applications, better product utilisation, real reflection of end-users’ need in the products and functionalities that transcend and across traditional products offer. They provide a new set of opportunities for all the actors with alteration of traditional structure and nature of competition among industries. These products redefine roles and relationships between different actors for much higher value creation. By reflecting the exact needs of users in the end products, MI dramatically improves output, efficiency, and utilisation of products.

The variability that MI creates in traditional product design, end-user needs, regulations from different authorities and standards can be challenging. Given the benefits MI provides to all the actors, these challenges are worth addressing. MI could be beneficial in a range of markets, with consumer electronics and furniture markets being examples that could readily benefit from the end-users’ perspective. MI with OPAP can be implemented in various products such as smartphones, smartwatches, and individualised furniture.
2.4.2 Roles of Different Actors in MI

Figure 2.4 illustrates the ecosystem for MI with the roles of all the actors that are actively involved in the product design process. The end-user is an integral part of the design phase and plays a driving role in making decisions related to supplier selection and product configuration. The design phase can be divided into two parts: Standardisation, where end-users have some constraints in playing with design put by other actors, and Individualisation, where end-users have all the freedom to select the modules and play with design as per their exact requirements. Role and involvement of the end-user in finalising the end product are as equal as other actors, so it becomes imperative to focus on the user experience which could influence the user’s decision of adopting that product. The user can be assisted by expert support with an interactive design platform.

**Figure 2.4 Roles of different actors in the MI Ecosystem**

Large original equipment manufacturers have the potential to offer a product platform with interfaces for a provision to add different modules. The large manufacturers would also provide few specific add-on modules for certain specific functionalities of the product. It is envisaged that these platform producers would also play an important role in the assembly of module options on the platform and after service of these products. The 3rd party module vendors will invent and manufacture module options for the end-users to opt and to integrate into the product platform. Every actor will have the opportunity to incorporate smart and innovative capabilities in module options. Specific add-on modules with specific nature and functionality will be provided when the end-users buy the product for the first time. Unknown
add-on modules would be provided to replace or upgrade the product as per the user’s requirements which were not thought of at the time of purchase. This kind of ecosystem shifts the competition basis from discrete end products to module options.

2.4.3 Comparison of MI with other customisation approaches

As mentioned in the earlier section, MI is a development on the existing user-centric customisation and personalisation approaches for product design. Table 2.2 shows how MI is different from existing product customisation and personalisation approaches.

*Table 2.2 Comparison with existing product customisation and personalisation approaches*

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Multipurpose products</th>
<th>Modular product Design</th>
<th>Product Platform &amp; Family Design</th>
<th>Product design for MI</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Product built</strong></td>
<td>Identical</td>
<td>Identical with a few change options.</td>
<td>Variants as per options provided by the manufacturer.</td>
<td>End-user-designed and individualised</td>
</tr>
<tr>
<td><strong>End-user's role</strong></td>
<td>Selection of an end-product</td>
<td>Selection of an end-product among offered options.</td>
<td>Selection of an end-product among offered options.</td>
<td>Active role in the whole design, from selecting platform, modules and the end-product.</td>
</tr>
<tr>
<td><strong>Requirement Fulfilment</strong></td>
<td>Might be useful in different</td>
<td>Can fulfil multiple</td>
<td>Can fulfil multiple requirements</td>
<td>Highly individualised</td>
</tr>
</tbody>
</table>
The variability that MI creates in traditional product design, end-user needs, regulations from different authorities and standards can be challenging. Given the benefits MI provides to all the actors, these challenges would be worth to address.

### 2.4.4 Innovation potential

The end product in product design for MI is the result of the creativity and innovation of the actors involved. Best of breed vendors will be able to supply more innovative modules for the products. Products that have been separate and distinct can become part of optimized systems of related products. From design idea to product end life, product design for MI provides many opportunities to innovate. The possible innovation potential with this new approach can be summarised as follows:

#### 2.4.4.1 Strategy & Methods

MI provides a platform to translate creative ideas quickly into innovative products and services. The role of customers is no more passive beneficiaries, but it is active value-adding partners (Goduscheit & Jorgensen, 2013). Products are a result of user-driven innovation, which fulfils all the individualisation requirements. At the same time, different third-party
vendors, i.e., smaller companies invent and produce innovative products with expertise in the respective field of modules. The more actors there are, the more innovative and useful can the product become (Koren, Hu, Gu, & Shpitalni, 2013). Access to resources is one of the main drivers of product innovation in MI.

2.4.4.2 Technology & Products

Participation of different actors with the latest technology in respective module production provides the most innovative products (Dodgson, Gann, & Salter, 2005). New products with new functions arise by technologies to be connected and shared. Experts in certain technology can provide their modules to the consumer without expertise in other areas of modules.

2.4.4.3 Processes & Organisation

MI motivates a merge between Technological and Sociological innovation. Smaller companies can become part of a large-scale production by sharing their modules. They can overcome the liability of smallness by opening up their innovation process and contributing to OPAP (Henkel, Schoberl, & Alexy, 2014). Innovative modules that deliver speed, transparency and ultimately solutions can be supplied more quickly in the market. One of the themes of MI is to build innovation ecosystems in the global context.

2.4.4.4 Society, Communication & Culture

MI provides product innovation for sustainable development. End products from MI are adaptable and upgradable. Open global product ecosystem provides opportunities for smaller companies around the globe to contribute with their innovative ideas. This will address and solve some of the challenges facing by the world today, such as resource and energy efficiency, urban production and demographic change (West et al., 2014).

In MI the creative act of the buyer yields the final product, and product offering depends on the creativity and innovation of many smaller companies that invent and produce modules. By this individualisation of customers’ needs, inherent characteristics such as individual taste, choice, and experience become an important integral part of product design and development. This paradigm of product design will create many new jobs in module production companies. Also, end user’s purchase intention and willingness to buy products
will enhance with this product design paradigm. More actors in the design process result in a more innovative and useful product. These products offer a rich, new set of value creation and innovation opportunities.

2.5 **Open Platform Architecture Products (OPAP)**

Open platform architecture products (OPAP) are key enablers for Product design for MI. OPAP are based on an open hardware platform with many interfaces for module integration. Figure 2.5 illustrates a typical schematic representation of an OPAP skeleton with interfaces, specific and unknown module options.

![Figure 2.5 Schematic representation of an OPAP with platform, interfaces and module options](image)

The platform is specified as the Skeleton in this research work. Specific module options show the modules which can be selected at the time of first use of the product by the end-users, where unknown module options demonstrate adaptability or those modules which can be added in future as per users change in requirement. Interfaces are represented by ‘I’ (1, 2, 3……n). Specific module options are represented by ‘MS’ (1, 2, 3……n, and 1, 2, 3……m), and unknown module options are represented by ‘MU’ (1, 2, 3……n, and 1, 2, 3……m). In this work, only specific module options are the primary focus for the development of the innovation toolkit.

Interfaces provide means of adaptability in OPAP. They provide flows of signal, motion, and energy between the platform and modules. Hu, Peng, and Gu (2014) suggested a method for the adaptable interface design where Interface types and design requirements are defined as
per the module types using a functional description method of interfaces. They also argued that different types of modules are replaced or upgraded in different frequencies and probabilities during the product life cycle, so different module interfaces should be considered differently. K. Chen and Liu (2005) investigated the interface strategy for modular products with concepts of external interfaces, internal interfaces and interface openness. In OPAP, it is envisaged that all the interfaces will be the same providing a universal means of attachment on modules on the platform and also to encourage wider opportunities for module options suppliers by generalising.

2.5.1 Comparison of OPAP with other product architectures used for product customisation

OPAP enables mass individualisation to be more practical and would help to realise and implement this approach in the market. These products are a development on existing product platform and similar product architectures used for product customisation. Table 2.3 summarises these different archetypes.

Table 2.3 Comparison of OPAP with different existing product architectures

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Multipurpose Products</th>
<th>Modular Products</th>
<th>Platform Products</th>
<th>Bespoke or One-of-a-kind products</th>
<th>Open Platform Architecture products</th>
</tr>
</thead>
<tbody>
<tr>
<td>Definitions</td>
<td>Products which combine several individual functions into a single unit.</td>
<td>Modular products refer to products, assemblies, and components that fulfil various functions through the combination of distinct building blocks.</td>
<td>A set of subsystems &amp; interfaces developed to form a common structure from which a stream of derivative products is derived (Mayer, 1997).</td>
<td>One-of-a-kind production (OKP) is a new manufacturin g approach to provide customized products based on requirements from individual customers, while maintaining</td>
<td>Comprises an open hardware platform by OEM and multiple modules from different smaller companies that are integrated with the platform as</td>
</tr>
<tr>
<td>Example</td>
<td>Swiss army knife</td>
<td>Modular table</td>
<td>Automatic drill machine</td>
<td>Window for house</td>
<td>Blocks (Smartwatch)</td>
</tr>
<tr>
<td>------------------------------</td>
<td>------------------</td>
<td>-----------------</td>
<td>--------------------------</td>
<td>------------------</td>
<td>---------------------</td>
</tr>
<tr>
<td>Developmen t</td>
<td>Often complex design relative to single-use products</td>
<td>Concurrent engineering possible (Multiple engineers can work on different modules at the same time)</td>
<td>Efficient and faster product development as different variants can be derived from the same manufacturing plan</td>
<td>Time consuming as manufacturing plans are different every time</td>
<td>Efficient and quicker with the use of Industry 4.0 and real-time connectivity</td>
</tr>
<tr>
<td>Time to the final product</td>
<td>As per market demand</td>
<td>As per market demand</td>
<td>Makes use of existing supply chain structure</td>
<td>Relatively slower</td>
<td>Quicker with real-time connectivity with different actors</td>
</tr>
<tr>
<td>Cost</td>
<td>Often expensive but Lesser cost for manufacturer and consumers in comparison with individual products</td>
<td>Component economies of scale but expensive than mass-produced products.</td>
<td>Likely to obtain higher performance for given cost as R&amp;D outlay spread over multiple products, can be benefitted from economies of scale</td>
<td>Likely to be expensive as one product, user specified.</td>
<td>Likely to be very affordable as different companies will provide the best price for each module.</td>
</tr>
<tr>
<td>Risk</td>
<td>Wasted performance</td>
<td>Reduced wasted performance</td>
<td>Reduced risk by using proven designs and processes, increase in</td>
<td>Reduced risk by careful consideration of every user’s requirements</td>
<td>Reduced risk by careful consideration of every user’s requirements</td>
</tr>
</tbody>
</table>

The quality and efficiency of mass production (Wortmann 1992, Tu 1997) per users’ choice.
<table>
<thead>
<tr>
<th>Fit to requirement</th>
<th>Might be useful in different situations but quality will be relatively lesser. Many times, these products are designed without considering critical aspects of customer requirements into account.</th>
<th>Can fulfil multiple requirements offered at the times of product pricing stage</th>
<th>Unlikely to be as good a fit to user requirement as bespoke</th>
<th>Exact fit to user requirements</th>
<th>Highly individualised and technologically advanced products</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upgrading</td>
<td>Not possible</td>
<td>Limited upgradation possible</td>
<td>Not possible</td>
<td>Easy to upgrade</td>
<td></td>
</tr>
<tr>
<td>Testing</td>
<td>As specified and slower due to complex design</td>
<td>Simple interfaces between modules provide simple testing of products</td>
<td>Ease of decoupling of components provide easy testing</td>
<td>As user specified at the time of product pricing</td>
<td>Simple interfaces between modules provide simple testing of products</td>
</tr>
<tr>
<td>First use convenience</td>
<td>For some products, multifunction is useful, but in the case of other products, single-use is more</td>
<td>Ease of first use as the product is with user selected modules</td>
<td>As specified by the manufactures</td>
<td>Ease of first use as the product is user specified</td>
<td>Ease of first use as the product is user-specified and completely individualised</td>
</tr>
</tbody>
</table>

wasted performance where standard products can be used.
2.5.2 Design aspirations from OPAP

Besides acting as a key enabler of product design for MI, OPAP provides immense opportunities including providing sustainable end products. OPAP offer adaptability and upgradability in products as the end product can be upgraded and reused by just changing the appropriate modules. These products provide means to address economic, environmental, and social aspects of sustainability. The report from the Center of Remanufacturing and Reuse (CRR, 2013) defined nine end-of-life (EOL) options:

<table>
<thead>
<tr>
<th>User interaction</th>
<th>Complex in comparison with single-use products</th>
<th>Easy interaction as the product is with user selected modules</th>
<th>As specified by the manufactures</th>
<th>Easy interaction as the product is user specified</th>
<th>Easy interaction use as the product is user-specified and completely individualised</th>
</tr>
</thead>
<tbody>
<tr>
<td>Usage</td>
<td>Useful in many situations but often redundant in terms of more than required functionality</td>
<td>Customised usage</td>
<td>Customised usage</td>
<td>User-specified so appropriate usage</td>
<td>Highly individualised products so optimum usage of products</td>
</tr>
<tr>
<td>Adaptability</td>
<td>Limited</td>
<td>Manufacturer-defined</td>
<td>Manufacturer-defined</td>
<td>User-defined but manufacturer controlled</td>
<td>Unlimited and user-defined</td>
</tr>
<tr>
<td>Serviceability</td>
<td>Relatively complex than single-use products</td>
<td>Ease of service due to differential consumption</td>
<td>Manufacturer-defined</td>
<td>User-defined but manufacturer controlled</td>
<td>Ease of service due to differential consumption</td>
</tr>
</tbody>
</table>
remanufacturing, refurbishing, repurposing, repair, reuse, recycling, composting, incineration, and landfill. OPAP provide sufficient means to address most of these EOL strategies. Module options used by users can be sold to a refurbishing market where they can be taken by other users at lower prices, thus, increasing the reach of expensive technologies to wider end-users across the globe. OPAP enable processes to be parallelised, different modules can be developed at the same time by various module options supplier. This makes the availability of end product very quick to be used by end-user.

2.6 INNOVATION TOOLKIT

Although MI has been considered a promising industrial product design paradigm to meet the increased aspiration level of today's customers, it also faces many challenges due to multidimensional variations of end products. To model these variations and capture innovation from different actors, a systematic approach and tools are required. Competitive pressure to accelerate product innovation, faster introduction to the market and increased product complexities have also motivated companies to utilise analytical design support systems for product design and development (Simpson & Martins, 2011). To address these challenges, the need for an innovation toolkit has been identified in this work. A networked innovation toolkit describes a design environment which enables and empowers actors to formulate their requirements iteratively and transfer these into a producible solution by an iterative process with continuous live networked support from other actors in the OPAP ecosystem.

By unification of design knowledge and information from various actors, the innovation toolkit provides aid in creating valuable resources for design improvement for the end-user and for future developments. This also serves as a design support system which provides solutions and suggestions for better design options. The innovation toolkit aspires to assist end-users in making better informed decisions, to anticipate customer satisfaction and adapt to customer delight. This toolkit also allows manufacturers to abandon their attempts to acquire detailed inherent needs of end-users and to focus their resources on providing end-users with platform exactly fit to demanded requirements.
2.6.1 Multi-level optimisation of OPAP

In addition to working as a design support system, Innovation toolkit comprises of multi-level optimisation model in this research. Optimisation of OPAP inherits all of the idiosyncrasies associated with single product optimisation including multiple objectives, constraints. However, optimisation of these products also deals with immense variability caused by multi-level participation from different actors. This involves additional intricacies such as the sequence of decisions from different actors, variability in capabilities of different module option suppliers, significantly high dimensionality. This causes additional challenges. Since OPAP is a new concept and in the absence of any existing optimisation model for these products in literature and in practice, established optimisation models of exiting product customisation methods (e.g., product family design, product platform) are used for reference.

J. Zhang, Xue, and Gu (2015) introduced a method for modelling of the platform, add-on modules, and open interfaces. Different constraints from many actors have to be taken into account while solving these models. Lin and Chen (2002) reviewed the literature on the modelling of constraints in product design with a discussion on several constraint-based design methods. Kreng and Lee (2004) used nonlinear programming to construct an objective function subjected to certain constraints and then applied a grouping genetic algorithm heuristic to search for an optimal modular design. Once the modelling of these individualised products is done, the next step is to identify the optimal configuration with optimal module options.

Optimisation of product family design (A. Khajavirad, Michalek, & Simpson, 2007) has been investigated in literature with different approaches. Simpson (2006) identified typical steps in product family optimisation: product family definition; product family optimisation problem formulation; product family optimisation problem solution; Evaluating the trade-off between different design alternatives and making a final decision. Khire, Wang, Bailey, Lin, and Simpson (2014) summarise the challenges involved with the formulation of a product family optimisation problem in an industrial setting. Insights from this work are extrapolated to formulate a part of the optimisation problem for OPAP. Khire et al. (2014) applied the all-in-one approach for product family optimisation. The all-in-one optimisation method considers all inputs and outputs of each individual product optimisation problem and combines them.
to form a large optimisation problem. This method also uses a commonality index to tie all the products together. A typical all-in-one optimisation problem scales the number of objectives, design variables, and constraints, as per the number of product variants. Due to considering all outputs together, this method does not consider the performance of individual products. This makes performance trade-off very difficult. Also, scaling becomes difficult as a number of product variants increases. The decomposition-based method is an alternative product family optimisation method which avoids these issues by considering each individual product performance explicitly.

In the decomposition-based approach for product family optimisation, the problem is decomposed into two levels: 1. Commonality optimisation and 2. Individual optimisation (Aida Khajavirad & Michalek, 2008). The commonality optimisation helps to determine the optimal platform configuration. The individual optimisation explores design space for product variants. Kim and Moon (2017) developed a multi-objective design optimisation approach to determine the optimal configuration of a product family with the consideration of sustainability. Fujita (2005) investigated into product family optimisation with combinatorial optimisation and parametric optimisation. Combinatorial optimisation is used to select the common components and module that forms the platform. Parametric optimisation is used to optimise both the platform and non-platform design variables. This approach provides the basis for the division of optimisation steps in multi-level optimisation of OPAP.

Xie, Henderson, and Kernahan (2005) developed models for engineering product configuration problems and solved them by constraints satisfaction. Levandowski, Jiao, and Johannesson (2015) developed a two-stage model of adaptable product platform considering design reuse and flexibility for engineering-to-order configuration design. A multi-objective optimisation algorithm was used for optimal configuration under uncertainty (Liu & Liu, 2010). Use of a genetic algorithm has been demonstrated for product platform optimisation by Xing and Abhary (2010) product upgradability design. Hong, Hu, Xue, Tu, and Xiong (2008) used genetic programming and parameter based optimisation to identify the optimal product configuration and its parameters for one-of-a-kind (OKP) production. The use of a genetic algorithm has also been used for multi-level optimisation for product family design with multi-level commonality (Huang, Li, & Schulze, 2008). In this work, genetic programming (Koza,
1992) is used for configuration optimisation, and penalty-based optimisation (Arora, 2017) is used for parameter optimisation.

2.7 CASE STUDIES

With any research, there is a choice to be made in terms of the sample, context or case study. A case study is selected as a mean of demonstrating developed frameworks in this thesis. The term case study is usually associated with a study that involves data from a real setting in practise. It is often considered equivalent to an observational study with one or very few cases. Yin (2017) characterised the case study as a research strategy rather than just a specific method. Baxter and Jack (2016) defined case study research as an approach “that facilitates exploration of a phenomenon within its context using a variety of data sources”. These data sources can be obtained in many ways. Yin (2017) summarises six common data sources: direct observations, interviews, archival records, product documents, participant observation, and physical artefacts. Case studies usually are based on mixed methods that means case study data may come from a variety of sources. Additional data sources may include translation and interpretation of interviews and transcriptions of authentic discourse (B. Meyer, 2015).

A case study helps to focus on a case product and retain a holistic and real-world perspective. This allows to investigate product life cycles, customer consumption behaviour, organisational and managerial aspects, and roles of different actors associated with the case product. Case study usually explores certain case products or phenomenon in depth, so the number of cases are usually very limited. The primary goal of case study research in this thesis is to develop an understanding about the applicability of developed innovation toolkit.

At the preliminary stage, this research identifies two case studies as suitable cases for investigating the new product design paradigm. These two case studies are explored on the qualitative scale to demonstrate the applicability of the proposed innovation toolkit. Product catalogues, specifications, companies’ documentation and other online and offline sources are used to explore various aspects of these two case studies. The third case study has been investigated on the parametric level to illustrate the effectiveness of the innovation toolkit on the existing market products. Interview results are used as a means of obtaining insights for this case study exploration and further parametric validation of introduced innovation toolkit.
Guidelines provided by Patton (2002) for formulating interview questions and conducting in-depth interviews are used in this thesis.
The cross-connection among various actors in the MI design process demands new and creative solutions. To better understand this new product design paradigm and capture innovation from all the actors, various systematic approaches are required. Each systematic approach would serve its own specific purpose. Kothari (2004) summaries these research approaches in the following basic categories: descriptive, analytical, applied, fundamental, qualitative, quantitative. These approaches have been used standalone or in one or other form of combinations such as exploratory, formulative, concept testing, industrial validation in the literature.

Concept testing is usually used in the concept development phase to test the success of a new product system or service (Smith & Albaum, 2005). Concept testing provides the direction and insights necessary to identify key areas, key benefits, and key challenges. The following sections summarise the research design and methods adopted for this research.

3.1 Overview of Research Methodology

As the previous chapter explains, MI is a relatively new concept for product design. Experimental study or case studies cannot be used without an existing implementation in the market or literature. Therefore, to investigate this uncertain context and answer the research question, only an exploratory study of current product design and customisation approaches with feedback from industry professionals and product design practitioners allows valid conclusions to be drawn. The methodology uses a qualitative exploration with quantitative analysis. Qualitative literature exploration is used to identify the key areas and components to be considered for the realisation and implementation of product design of MI with OPAP. This qualitative exploration is also used for designing a questionnaire survey for industrial feedback and implication of this approach.

To capture networked innovation from all the actors and to provide an optimised OPAP, an innovation toolkit is developed in the third phase of the research. This toolkit is further validated on the theoretical and parametric level with the help of three case studies.
3.2 Key areas and components to be considered

One of the objectives of this thesis is to identify different key areas and components needed to be focused on to realise and convert this innovative approach of MI into industrial practice. This is done by investigation and exploration of current product design approaches. Major areas of research in product customisation, user-centric customisation, adaptable products, smart and connected products, open architecture products, smart manufacturing, and other related areas are explored through published articles, books, companies’ profiles, and other online articles. The result will be a concise compendium of the relevant areas need to be focused for this new product design paradigm.

The end product form MI will be highly individualised across different industrial sectors. With taking the theme of Innovation 4.0 as a basis, various areas of MI that need to be focused on are categorised as follows:

1. Changes in traditional product design and customisation approaches that need to be focused on

2. Components that need to be focused on

3. Technologies that need to be integrated

3.3 Industrial questionnaire survey

The end products from product design for MI offer a vibrant, new set of opportunities for creating value and innovation. Based on the exploratory study of relevant literature and current product design and customisation methods, a web-based industrial questionnaire survey constituting multiple choice questions and text answer questions has been designed. As Patton (2002) describes, a questionnaire allows to enter into respondents perspective of the area to be investigated. Feedback on critical issues of product design for MI will provide an industrial insight on the topic. This will be used to develop the approach further with practical implications. Most of the critical points are based on general industrial product design. They are not industry specific. It will help to decide on the direction of research development. Guidelines on the formulation of good questions and construction of various
open and closed questions provided by Dillman (2011) are used to design the questionnaire for this survey.

The online survey can be taken via the following link:

https://imperial.eu.qualtrics.com/SE/?SID=SV_8nRYVfHnyv2za8R

3.3.1 Survey design

A web-based industrial questionnaire survey constituting multiple choice questions and text answer questions have been designed to obtain more extensive insights and to reach global product design companies. Text questions were included to obtain insights which might overlook by remaining questions. To address different aspects of MI, the survey is divided into the following four sections:

3.3.1.1 Product Design for Mass Individualisation (MI)

This section investigates different aspects of MI such as familiarity with the context and concept in the market, suitability to industry type, innovation potential. This section is also designed to obtain some broad details about participants including their industrial background and willingness to use end products from MI. As there is no existing application of this approach in the market, responses from this section would frame the basis for further development of this approach. This section also explores the possibilities of enhancement in the intention and willingness of end users to buy products from this innovative approach of MI.

3.3.1.2 Product Design Innovation

One of the key benefits of product design for MI is a significant contribution to product design innovation. The second section explores different product design innovation potential. As MI encourages and provides a platform to all the actors to participate and contribute towards the final product, this also provides potential to innovate at multiple levels. These levels include a reflection of creativity and innovation of end users, of module option suppliers and of platform producers. This section also investigates the possibility of sustainable product innovation by product design for MI.
3.3.1.3 *Strategical and Technological integration*

The product design for MI aims to encourage networked innovation with strategical and technological integration of all the actors. This section investigates various aspects associated with this kind of integration and their influence on the product design ecosystem. This section explores important issues such as access to resources, competition between actors, the organisational structure required for MI ecosystem, opportunities for smaller companies as module option suppliers to be a part of a larger industrial structure.

3.3.1.4 *Practical suggestions*

This section is an attempt to capture details not addressed in previous sections. As this survey is designed to gain insights from product design practitioners, this section provides an opportunity for participants to respond on some practical issues which one can only come across after hands-on experience. These practical issues involve a range of situations such as intellectual property right conflicts, practical impediments, allocation of resources.

These sections were selected to collect a wide variety of insights touching different critical points of this relatively new product design paradigm. Most of the answers to multiple choice questions were measured on a categorical scale with an option of additional comments. The categorical scale was divided into five to seven categories, with the middle category representing a neutral standpoint. Both sides of the middle category were used to show different levels of agreement and disagreement. Table 3.1 summaries all the questions, covering a range of aspects and insights, included in this survey.

*Table 3.1 Survey questionnaire*

<table>
<thead>
<tr>
<th>Product Design for Mass Individualisation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Are you familiar with the concept of product design for MI (Mass Individualisation)?</td>
</tr>
<tr>
<td>2. What kind of industry are you affiliated with?</td>
</tr>
<tr>
<td>3. Which statement best describes how innovative could be the new product design paradigm (MI) for product design?</td>
</tr>
</tbody>
</table>
4. Which statement best describes how relevant the idea of product design for MI is for your industry?

5. What do you think about the suitability of this product design concept for a particular type of industry?

6. This product design paradigm would enhance the intention and willingness of end users to buy products. How would you agree with this statement?

7. If you had the opportunity, would you consider purchasing a product designed with this approach?

### Product Design Innovation

8. Product design for MI encourages creativity and innovation. Do you agree with this statement?

9. Which statement best describes how effective you think the new product design paradigm (MI) would be for satisfying customers' needs?

10. The inclusion of so many actors in product design opens the door for innovation opportunities. How do you agree with this statement?

11. Different participant companies with different expertise will be able to provide their best in field modules for users which will make the product most advanced and innovative? How would you agree with this statement?

12. This product design paradigm also provides an innovative means for sustainable product design as the end product is adaptable and upgradable. Do you agree with this statement?

13. End users can develop a product module for their products and can contribute towards product innovation. Do you agree with this statement?

### Strategical and Technological Innovation

14. Open platform architecture products (OPAP) expand the industrial boundaries and bring together different firms with their own expertise on a single platform. How
would you consider that this is an opportunity for smaller companies to be a part of a larger system?

15. Product design for MI changes the industrial structure from vertical (different actors in a single organisation) to horizontal (different actors in different organisations). How do you think it affects the innovation in organisations?

16. This new product design paradigm helps to encourage positive competition between companies by giving them equal opportunities to invent and product modules. Do you agree with this statement?

17. Access to resources by cross networking between different actors is one of the key advantages of this product design paradigm. How important you think this would be for product innovation?

18. Networking between different actors at the same level and guidance by the platform manufacturers provides the best of the innovative technology available. Do you agree with this statement?

19. This approach would decrease the technological uncertainty caused by rapidly changing product technology in the market? Do you agree with this statement?

**Practical Suggestions**

20. This approach has the potential to replace current industrial product design practices?

21. What would be the barriers to achieving the full innovation potential of this paradigm?

22. What would be the concept improvements over current industrial product design approaches?

23. This product design paradigm would not only provide an innovative product design process, but also influences society and economy by providing more jobs and more accessible products. Do you agree with this statement?
24. How do you think firms should manage ownership of intellectual property rights when these many actors (other firms) are involved?

25. Can you identify any other practical impediments overlooked by this survey for this new approach?

26. Would it be possible for a large original equipment manufacturer (platform producer) to adopt a traditional product design and product design for MI together?

27. If firms adopt both these approaches, how should a firm allocate its resources between them?

28. Which consumer segment should be targeted by this new approach?

29. How can a firm optimise the process of product design for MI?

3.3.2 Survey response and analysis

To obtain industrial insights, consumer product design companies (350) from different countries are selected as respondents. An invitation email was sent to respondents to take part in this survey. Access to the questionnaire survey was given to participants by a link in the invitation email, to protect participants’ privacy. All the responses were recorded anonymously. This privacy protocol was mentioned in the invitation email. Participants’ consent to participate in the survey was implied by completing and submitting the online questionnaire.

Figure 3.1 illustrates the industry splits of the invited survey respondents, across different sectors. Before sending the survey to participants, the questionnaire was tested with participants working with or aware of the product design for MI. Feedback from this pre-test was used to modify the questionnaire more appropriately. Responses were recorded and used further for descriptive analysis. This analysis has been interpreted and presented in the following chapter to reflect on industrial insights and implications.
3.4 NETWORKED INNOVATION TOOLKIT TO IDENTIFY THE OPTIMAL DESIGN OF OPAP

A networked innovation toolkit describes a design environment which enables and empowers actors to formulate their requirements iteratively and transfer these into a producible solution by an iterative process with continuous live networked support from other actors in the OPAP ecosystem (Sikhwal & Childs, 2019). The function of one module or module system can be optimised with other related modules or module systems with this innovation toolkit. A multi-level optimisation model is developed for this innovation toolkit to identify the best design configuration with optimal module options which satisfies all the requirements of the end-user. Based on the needs in the development of the end-products in MI, the following aims were set for this innovation toolkit:

- Adaption and reflection of user ideas into the end products.
- Integration of technical-functional and product-strategic approaches of various actors.
- Provision of a design support system for end-users and other actors for decision making at various phases of product development.
• Fostering active participation of actors, providing a mean for contributing directly to end product.
• The flexibility of tailored support to different product scenarios.

3.4.1 Different Phases of Innovation Toolkit

Figure 3.2 depicts the approach for multi-level optimisation for networked innovation toolkits, based on the five phases of design for open innovation (Holle & Lindemann, 2015).

![Figure 3.2 Different phases of Innovation toolkit]

3.4.1.1 Platform Analysis

This phase consists of an analysis of product type and category which provides the basis for analysis of the required platform with a required number of interfaces.

3.4.1.2 End-user Analysis

Acquisition and analysis of individualisation needs, and derivation of modules and interfaces which is required for individualised products. This phase is basis for platform and module options for selected product type.

3.4.1.3 Conflict Analysis

Determination of individualisation potential based on weighted criteria, and derivation of alternative requirements from end-users, modules manufacturer and platform manufacturer. This phase is the basis for determination of constraints for a multi-level optimisation model.
3.4.1.4  **Product Configuration Modification**

Definition of Alternative Product Configurations, Assessment of Alternative Product Configurations, and Selection of suitable Product Configuration with an optimised combination of modules interfaced with the platform.

3.4.1.5  **Validation of Product Configuration Modification**

Validation of product configuration modification by the innovation toolkit and Feedback for iterative improvement of product configurations from the end-user.

3.5  **CASE STUDY VALIDATION OF INNOVATION TOOLKIT**

Case study validation is used to validate and demonstrate the applicability of proposed innovation toolkit in this research. Three product platforms have been identified to illustrate the effectiveness of the proposed innovation toolkit to obtain an optimised and highly individualised end products. At the preliminary stage of innovation toolkit validation, two case studies are explored on the qualitative scale to demonstrate the applicability of the proposed innovation toolkit. Product catalogues, specifications, companies documentation, and other online and offline sources are used to explore various aspects of these two case studies.

The third case study has been investigated on the parametric level to illustrate the effectiveness of the innovation toolkit on the existing market products. Based on the insights obtained from the first two case studies and industrial engagement, an interview is designed. Interview results are used as a means of obtaining insights for the third case study exploration and further parametric validation of introduced innovation toolkit.

The standardised open-ended or semi-structured interview is designed covering various aspects of the application of an OPAP in consumer electronics. Based on the industrial questionnaire outputs from the second phase of this research, an OPAP consumer electronics product, BLOCKS has been chosen for this case study validation. BLOCKS is a modular smartwatch company with OPAP design approach. A BLOCKS smartwatch has two parts: the Core and the Strap. The idea of the core is similar to the idea of Platform in this study. The strap is made of several customer selected modules. Customers can choose the modules which best suit their lifestyle and needs. Different blocks (modules) with a specific
functionality are added to the core (platform) to individualise the final smartwatch. Blocks can be exchanged for new applications as and when needed.

The interview is further modelled to this specific product to capture as many as insights necessary to form an overall understanding of the applicability of the proposed innovation toolkit on this product. Table 3.2 summaries various questions of this interview. Questions start with obtaining insights on the positioning of BLOCKS in MI space. Along with the details required for innovation toolkit validation, some other questions regarding benefits, scope and future direction of MI are also included in this interview. These questions provided a framework within which the respondents can express their current understanding of MI and the understanding of MI after getting familiar with the first two phases of this research. The last phase of the interview is used to get various parametric details to input in the multi-level optimisation model of developed innovation toolkit.

Table 3.2 Interview questions for Case Study Validation

<table>
<thead>
<tr>
<th>Interview questions for Case Study Validation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. What was the opportunity you recognised when starting BLOCKS?</td>
</tr>
<tr>
<td>2. What do you believe are the two main success factors behind Blocks?</td>
</tr>
<tr>
<td>3. What changes affecting the mass individualisation industry have you recognised over the last years?</td>
</tr>
<tr>
<td>4. Which is one technological, economic or social trend influencing your business most?</td>
</tr>
<tr>
<td>5. Can you explain a bit more how the mass individualisation of pathways in consumer electronics works?</td>
</tr>
<tr>
<td>6. What are your core factors in the configuration process, also with regard to providing excellent customer experience?</td>
</tr>
<tr>
<td>7. What was your biggest mistake?</td>
</tr>
<tr>
<td>8. What are the success factors of mass individualisation companies?</td>
</tr>
<tr>
<td>9. How do you access the future of Mass Individualisation? Can there be too much of a good thing?</td>
</tr>
<tr>
<td>10. What questions are open in mass individualisation research? What is going to be the next research phase?</td>
</tr>
<tr>
<td>Question</td>
</tr>
<tr>
<td>------------------------------------------------------------------------</td>
</tr>
<tr>
<td>11. What do you recommend to a person who is doing research in this domain?</td>
</tr>
<tr>
<td>12. What one advice you would give to an ambitious entrepreneur who wants to work with this kind of products?</td>
</tr>
</tbody>
</table>
4 RESEARCH FINDINGS AND DISCUSSION

This chapter presents an explorative study of current product design and customisation methods, followed by an industrial questionnaire that provided insights and a new basis for developing the relatively new approach of MI and framework for the innovation toolkit for optimal OPAP.

4.1 KEY AREA AND COMPONENTS TO BE CONSIDERED FOR THE INDUSTRIAL IMPLICATION

The explorative literature analysis identified various key areas, and components that need to be considered for application in a commercial context. Underlying factors include end-user’s willingness and preparedness to be integrated into the process of product co-design and co-creation, near-universal availability of the Internet, development of information technologies, evolving product architecture, modern manufacturing systems, such as reconfigurable flexible manufacturing. Figure 4.1 illustrates the findings of the explorative literature analysis of existing product design and customisation approaches.

![Figure 4.1 Key areas to be considered for industrial implication](image-url)
4.1.1 Changes in traditional product design and customisation approaches

The realisation of product design for MI with OPAP requires a whole set of new design principles, such as cross connected design support system, access to everyone. The following changes in traditional product design approaches are identified to realise the new product innovation paradigm:

4.1.1.1 Context

Unlike traditional approaches to product design, MI consists of horizontal networking between different actors. Every actor has an equal role in the final product and innovation process, and the end product is the end result of the creativity and innovation of various actors. Existing risk assessment and profit sharing models (Lo Nigro & Abbate, 2011) can be restructured for these horizontal networks. Openness and networking between actors of MI must be seen as an opportunity than a challenge.

4.1.1.2 Ecosystem

The MI ecosystem consists of three main actors: end-user, platform producer and various module options providing companies (such as third-party vendors, independent module developers). All the actors can be mapped with a multi-level and cross-connected ecosystem framework to disentangle and manage the relationship among them. This framework would include the expectations and goals of participating stakeholders/actors. Strategies developed for value co-creation in a multi-stakeholders atmosphere for a firm (Nudurupati, Bhattacharya, Lascelles, & Caton, 2015) can be used as a basis for the ecosystem.

4.1.1.3 Perspective

An autonomous car should be more than a car which includes one or many computers. It could be seen as a computer on wheels. This simplified sketch is characteristic for other products and application areas as well, including MI. Networking between all actors becomes a central feature in this new approach. Everybody and everything is connected anytime everywhere. This approach would also encourage responsible product consumption, sharing economy and other socio-technical benefits. Social and technological innovation are closer than previously encountered and development of MI benefits from this.
4.1.1.4 Vendor

Smaller companies play an important role as third-party vendors. The inclusion of various module options vendors towards the end product helps to intensify the innovation in the product design and development process (Gulati, 2010; Wynstra & Pierick, 2000). Interactive design support system networked with end-user, platform producers, institutes and other experts explore and investigate possibilities of new practices and artefacts via interactive processes.

4.1.1.5 Discipline

This new approach encourages excellence through the interdisciplinary network. Highly sophisticated, socio-technical systems have to be developed as a central theme with a collaboration of various academic disciplines expert and institutions. To realise and implement this approach in the market, future designers will require to look further beyond their expertise and traditional business models. Roles of connectivity and data specialists, energy and data specialists will play important roles in design support systems in any MI ecosystem. MI with OPAP provides the incentive for adaptability to rapid innovation cycles, encouraging creativity than expert know-how.

4.1.1.6 Competition

A healthy competition between all the actors needs to be motivated for improved design and innovation. Approaches like competition in the multi-sided platform market channel (De Matta, Lowe, & Zhang, 2017) can be expanded considering different roles and settings of various actors of MI ecosystem. The half-life of knowledge is shortening rapidly, providing platform producers and module options suppliers to come up with better and more innovative solutions.

4.1.1.7 Access

The traditional close access in product design approaches has to be changed. Horizontal networking of various actors needs to be strengthened by access to all essential information to all the actors. Access to information and resources is one of the main drivers of networked innovation in the product design for MI with OPAP. Different actors would pursue joint
ownership of product data in order to provide access to relevant actors to produce module options requested by end users.

Change in the ecosystem is investigated further thoroughly as a part of this research for strategic and technological integration.

**4.1.2 Components that need to be focused on**

Development of different components of MI ecosystem requires innovative means of design, manufacturing and relevant infrastructure that have not been typically present in existing companies. The following areas are identified to focus the approach to the new paradigm:

**4.1.2.1 Design & development**

The design is the most critical phase of any product. The end-user has a direct role in the product design and development in MI, unlike traditional product design approaches. Product development processes in MI will need to accommodate post-purchase design changes more quickly and efficiently. With an interactive design support system, they can select only those modules which can fulfil the desired requirements, thus designing a highly individualised end product. This research finds that this will be an iterative process; the end-user will select modules for the platform and then different module options will be provided by 3rd party vendors or module option suppliers. Decentralized decision-making and customer-centric innovations would require new systematic approaches. An innovation toolkit with multi-level optimisation will be employed for a more feasible and efficient end product, within constraints provided by smaller companies and platform producers. The main idea behind value creation through MI is that the more stakeholders there are, the more innovative and technologically advanced can the product become.

**4.1.2.2 Manufacturing**

In MI, the end product is made of platform, interfaces and modules/module options. These different components will be manufactured in different places. It is envisaged that the platform along with different interfaces will be manufactured by large manufacturers. Different interfaces include electrical, software and mechanical interfaces. Module options will be provided by different smaller companies with their own manufacturing facilities. This type of manufacturing needs more responsiveness in production and advanced
reconfigurable manufacturing systems (RMS) that can manufacture a variety of products with existing facilities (Ortega Jimenez, Machuca, Garrido-Vega, & Filippini, 2015; Wei, Song, & Wang, 2017). Decentralisation with simultaneous globalisation provided by MI ecosystem has its own challenges which need new development on existing supply chain approaches. Current manufacturing enterprises need to be equipped with latest practices like the internet of things to produce product timely and in an accurate manner. Internet of manufacturing things (IoMT) is one such example (G. Zhang, Wang, Sun, Si, & Yang, 2015).

4.1.2.3 Assembly

A new networked assembly line, capable of assembling different module options provided by different 3rd party vendors on the platforms as per end-user needs, is required. Different suppliers across the globe will offer module options as requested. It is envisaged in investigation that the final end-product can be assembled by platform manufacturers.

4.1.2.4 After services

This approach will require a new and innovative method of after service. A service point needs to be created which can be accessed by platform manufacturers to facilitate iterative communication between end-users and module options suppliers.

4.1.2.5 Sustainability, Adaptability, Upgradability

Product design for MI contributes to the circular economy in many ways. In MI, the end product is most individualised. End-users select only those module options which fulfil their exact requirements. This reduces the overproduction of the modules or products. It is easy to use the product for a more extended time period as the product is a precise fit to the needs. End-users can also change the modules as per the change in requirements. Thus, the end product is highly adaptable. Used modules can be put again in the marketplace for other users to use. Products can be upgraded just by replacing the existing module with an updated module, instead of changing the entire product; it would significantly contribute towards sustainable product design.

Design of OPAP is in the main focus for this work to produce an optimised end product which will satisfy all the requirements of the end users as well as will be feasible to produce for platform and modules manufacturers.
4.1.3 Technologies that need to be integrated

Technologies are identified as one of the factors that facilities and make the concept, the networked innovation in MI far more practical. The improved speed, processing power, evolution of customer relationship management (CRM) as a strategy, improvements in enterprise resource planning (ERP) software consistent with individualised needs, data warehousing, connectivity, and interfaces provide the required support to transit to new product design paradigm. New technologies allow for new ways to collaborate and coordinate across various discipline and between actors. These technologies help to create and develop new environments for actors to think about new options, to interact iteratively or to experiments with a different combination of module options into the end product. Advanced information and communications technologies have enabled an even faster exchange of distributed sources. These technologies not only provide direct means to facilitate the support system for MI but also helps shape the strategic orientation of industrial firms towards OPAP. They help to forge closer links between market information and further technology development. The following technologies are identified as key contributors to this new product innovation process:

4.1.3.1 Data mining, AI and IoT

Real-time connectivity with users and vendors, cloud computing, fast processing of data, big data, data mining, data visualisation, augmented reality (AR), 3D printing, internationalisation of technologies, artificial intelligence (AI) and Internet of things (IoT) are few key technological enablers to realise and implement this new product design approach. Internet-based innovation platforms and intermediaries will assist in identifying patterns in consumption data to find opportunities and challenges. Access to these data and the demand pattern of users accelerate the process of networked innovation. Thousands of inventors and designers will be able to work together on cloud computing with different data mining resources to generate innovative solutions for this new product design paradigm. Technologies like AR and 3D printing enable fast visualisation of end-products. With the help of AI, various products are able to perceive their environment and take actions to maximise their chances of successfully achieving their targets. These products will collect the information and act as per change in user preferences.
One other key enabler for this innovative product design approach is the Internet of Things (IoT). This refers to the interconnection of computing capability in everybody objects or in other terms, connecting devices over the internet. An IoT ecosystem consists of web-enabled smart devices that collect data with embedded processors and sensors, send these data to an IoT gateway to analyse locally or on cloud and then act accordingly. IoT makes strategies like MI far more practical and cost-efficient. Information can be shared in real time between all the actors. End-users can select the modules they want and opt to integrate selected module option into the platform in real time. Module option suppliers and platform providers can see what modules are being ordered, and with rapid systems retooling and reconfiguration adjust their manufacturing and assembly line appropriately (Lu & Cecil, 2016). Wang, Lin, Zhong, and Xu (2019) proposed a new cloud platform to integrate hard resources such as 3D printers and materials, and soft resources such as the know-how and test data to provide supports on 3D printing, design and process planning.

Application of IoT for Product Lifecycle management (Cai et al., 2014) and business models (Leminen, Westerlund, Rajahonka, & Siuruainen, 2012) have been explored in the literature. Industry 4.0 and innovation 4.0 are all two further developments of ICT with the Internet of

Figure 4.2 Core technologies to be focused on
Things as the key enabler. Figure 4.2 summarises various technologies which would assist the realisation and implementation of the next innovative product design paradigm.

These technologies not only help to monitor the overall business processes but also help to improve overall customer experience, enhance the productivity of associated actors, generate more revenue and adapt business models accordingly. A new strategic framework for the optimised application of various technological tools needs to be developed.

4.1.3.2 Innovation toolkit

This research identifies the need of an innovation toolkit which would provide a design support system to funnel design potential to the end-user, and a framework to determine the optimal OPAP with optimal module options on the platform. It would guide the end-user within specific frameworks to choose modules for the platform according to their exact needs. End-users can also use this toolkit to better understand various product scenarios, i.e. Web training can be used to learn specific specialised skills required for a custom design. This will help end-users to present their latent requirements that conventional customer requirement research tools cannot provide. The innovation toolkit can be further developed to make sure that final end product can be assembled on the planned production lines. It would also support a whole range of value-adding services, such as web services, resource planning, and end-user relations management.

4.1.3.3 Modelling and simulation

Modelling and simulation have been an essential part of the product design and development process. It allows real-time, execution level events to be represented, investigated, analysed and understood. Simulation provides a rich environment for testing and analysing different approaches to operating strategies which could be effective (Dodgson, Gann, & Salter, 2006). The aim of having a modelling system is to provide a platform for product specifications change during the design stage. This makes it possible to represent, analyse and redesign the end product before going to prototypes. Configuration-oriented product modelling for made to order manufacturing (Jinsong, Qifu, Li, & Yifang, 2005) can be used as a basis to approach modelling in this approach. New modelling tool has to be developed that makes it easier for different actors to access the design, iterate design modifications and receive continuous feedback from other actors in the ecosystem.
4.1.3.4 Product realisation

Augmented reality, rapid prototyping, and additive manufacturing are some of the critical processors that enable the realisation of the end product before the final manufacturing and assembly. However, in order to realise end product development, a new product realisation tool for end-users needs to be developed which can provide all the liberty to experience the end product and to give continuous feedback on that experience to 3rd party suppliers of module options and platform manufacturers. This can be built upon some available commercial platforms which provide this kind of communication between actors, i.e., Second life (SecondLife, 2017). Another such example is virtual reality shopping malls by P&G to test consumer reaction to its products compared to competitors (Dodgson et al., 2006).

Networked innovation toolkit has been further explored for the technological integration in the third phase of this research. A real-time connected toolkit with live feedback will be developed, where the end-user can select and integrate the modules for innovative product design.

4.2 Industrial implications

A questionnaire survey, based on the insights from exploratory literature analysis and identification of key areas and components for implementation of MI, has been conducted. 50 responses were recorded which yielded an adequate amount of valuable information about the innovative approach of product design for MI. These responses have been analysed descriptively and statistically to understand the industrial implication. Insights from this analysis are used to further develop the approach. The Appendix summarises the questionnaire along with the categorical and text responses. Different results in terms of responses along with analysis have been explained in the following sections.

The first five questions aimed at obtaining insights on the current product design approaches and the significance of the innovative product design approach of MI. It can be seen in the responses to Q.1 that majority of the respondents are unfamiliar with the MI. It can be explained from the fact that product design for MI is a relatively new product design approach which requires further research and development in different aspects of the approach. This work provides an initial framework in that direction. Q.2 responses provide an indication that
most of the participants are from consumer electronics companies. This is consistent with the assertions made earlier that consumer electronics goods would be the starting point for the market implementation of the product design for MI. Responses to Q.3 are encouraging and consistent with the objective of this article that product design for MI would lead to more innovative end products tailored to the exact needs of the end-users. Question 4 was designed to understand the applicability of this approach. Responses to this question provide mixed agreement. It can be explained from the fact that some market segments, probably consumer electronics companies as demonstrated in the Q.2 responses, would regard product design for MI as a more beneficial product design approach. Q.5 was designed to understand the application of MI to types of industry. 27% of responses agreed with the suitability of MI with all types of industries, but interestingly similar responses showed the Fashion industry, the Furniture industry and Consumer electronics as leading beneficiaries. This could be inspired by the existing application of product customisation in these areas.

Responses to Q.6 were significant in providing motivation for this research and an associated paper (R. K. Sikhwal & P. R. N. Childs, 2017a), with 80% of responses indicating that MI would increase the intention and willingness of the end users to buy end products produced by this approach. As opposed to other existing customisation approaches, MI provides end-user a platform to be a direct part of the product design and development process. It facilitates end-users to invent and work on their own idea and contribute towards the product. Q.7 was included to obtain an idea about the acceptability of the end product by this approach. Given the benefits of MI with open platform architecture, more than 80% responses show that respondents would consider using a product designed with this approach.

![Figure 4.3](image)

*Figure 4.3 Responses to Q.8, ‘Product design for MI encourages creativity and innovation…………… this statement?’*
Responses to Q.8 are shown in Figure 4.3. These responses are very motivating as 76% of responses are in some degree of agreement with the idea that MI will encourage creativity and innovation towards producing a highly individualised end product. This creativity and innovation would play a vital role at different stages of design and development. Responses to Q.9 confirm that product design for MI will satisfy customers’ needs in the best possible way. It is evident from the fact that customers will be able to select the specific modules as per their exact requirements into the end product.

Table 4.1 illustrates a comparison of responses provided for Q.6 and Q.9. For ease of analysis of responses of Q.6, somewhat agree and agree responses are bundled together under agree column, so thus the somewhat disagree and disagree one under disagree column. Similarly, for the responses to Q.9, very effective and extremely effective responses are bundled together under the column of very effective response, so thus slightly effective and moderately effective under the moderately effective column. It is interesting to note that majority of responses which agree with the fact that MI would be moderately effective to very effective, also agree with the notion that it would increase the intention and willingness of the end-user to buy end products designed with this approach. This co-relation emphasises that customers would be much happier to purchase a product if it is more individualised in terms of satisfying individual needs. This proves the potential of MI with OPAP in addressing market to one phenomenon.

Table 4.1 Comparison of responses of Q.6 and Q.9 (responses are in percentages)

<table>
<thead>
<tr>
<th>Effectiveness of MI in satisfying end-users needs (Q.9)</th>
<th>Enhancement of the intention and willingness of end-users to buy products (Q.6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very effective</td>
<td>Strongly agree</td>
</tr>
<tr>
<td>33</td>
<td>58</td>
</tr>
<tr>
<td>Moderately effective</td>
<td>8</td>
</tr>
<tr>
<td>Not effective at all</td>
<td>0</td>
</tr>
</tbody>
</table>
It can be seen in the responses to Q.10 that these are in line with the responses to the previous question. It indicates that the incorporation of so many actors towards getting end product unlocks many innovation possibilities. It was envisaged in first phase of the literature analysis in earlier sections that different module options providing companies will be able to provide the most advanced and innovative products by this approach. Responses in the agreement side strengthen that analysis, but almost similar responses in the negative side, show that it might depend upon many factors, including various functional constraints put forward by the platform manufacturer and other module option providers. Q.12 responses are illustrated in Figure 4.4. These responses strengthen the notion that MI will be able to offer an innovative means towards sustainable and adaptable product design, as greater than 50% responses are in agreement and 27% responses are on neutral standpoint.

Figure 4.4 Responses to Q.12, ‘This product design paradigm also…………………this statement?’

32% of the responses to Q.13 are in agreement with the notion that the end users will be motivated enough and will contribute towards product innovation. It is evident from the fact that they will be able to select and even produce module options. However, 28% of responses are only slightly agree with this question. It could be inspired by the fact that end users may not possess enough skills set and understanding including acquiring appropriate requirements and generating suitable module options.

Table 4.2 provides a very useful comparison of Q.8 with Q.10 and Q.13. For ease of analysis of responses, somewhat agree and agree responses are bundled together under agree column, so thus the somewhat disagree and disagree one under disagree column. Q.8 explores the possible encouragement to creativity and innovation in the product design process provided by MI, and Q.10 and Q.13 explore the reason behind that encouragement. It is evident from this table that percentage of responses which are in agreement side of the
idea that MI motivates creativity and innovation, also agree with the fact that this encouragement to creativity and innovation might be because so many active actors are included in the product design process and also because of end-user’s direct contribution.

Table 4.2 Comparison of responses of Q.8 with Q.10 and Q.13 (responses are in percentages)

<table>
<thead>
<tr>
<th>MI Encourages Creativity and Innovation (Q.8)</th>
<th>The inclusion of so many actors provide Innovation opportunities (Q.10)</th>
<th>End -user can also contribute towards Product Innovation (Q.13)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strongly agree</td>
<td>Strongly agree</td>
<td>Agree</td>
</tr>
<tr>
<td>Strongly agree</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Agree</td>
<td>0</td>
<td>80</td>
</tr>
<tr>
<td>Neither agree nor disagree</td>
<td>17</td>
<td>33</td>
</tr>
<tr>
<td>Disagree</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Strongly disagree</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Responses to Q.8, Q.10 and Q.13 are further analysed to see any statistical difference between these responses. IBM SPSS is used to carry out this statistical analysis. A non-parametric test, known as the Mann-Whitney U test is selected for this statistical analysis. This is used to compare differences between two independent groups when the dependent variable is ordinal. ‘No difference between responses from these two groups/questions’ is used as the null hypothesis.

Table 4.3 Test Statistics for the responses of Q. 8 and Q. 10

<table>
<thead>
<tr>
<th>Test Statistics²</th>
<th>Level of Agreement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mann-Whitney U</td>
<td>270.000</td>
</tr>
<tr>
<td>Z</td>
<td>-.412</td>
</tr>
<tr>
<td>Asymp. Sig. (2-tailed)</td>
<td>.680</td>
</tr>
</tbody>
</table>

Tables 4.3 and 4.4 show various outputs of the Mann-Whitney U test. Since the value of p>0.05, the null hypothesis can be accepted. From this data, it can be concluded that there is
no statistically significant difference between responses of Q.8 and Q.10, similarly for Q.8 and Q.13.

**Table 4.4 Test Statistics for the responses of Q. 8 and Q. 13**

<table>
<thead>
<tr>
<th>Test Statistics</th>
<th>Level of Agreement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mann-Whitney U</td>
<td>263.500</td>
</tr>
<tr>
<td>Z</td>
<td>-0.839</td>
</tr>
<tr>
<td>Asymp. Sig. (2-tailed)</td>
<td>0.402</td>
</tr>
</tbody>
</table>

a. Grouping Variable: Question Number 8 vs 13

The responses to Q.14 suggest that MI provides a mean of expansion of industrial borders and bring various companies with particular competence together on a solitary platform. Above 50% of responses agree with the notion that this approach provides a basis for this. Response to Q.15 to Q.18 highlighted a few changes in the business strategies that will happen due to MI. Responses to Q.15 were mixed in nature in responses. This question was designed to gain insights on the idea that MI will encourage innovation in terms of organisational structure. A possible explanation is that MI has not been implemented in the market with an organisational structures. It can be seen in the responses to Q.16 that MI motivates positive competition in module options suppliers (i.e., 3rd party vendors).

Most of the responses to Q.17 indicate that resource accessibility by cross networking in between various actors is essential for innovation in product design. Q.18 with responses is depicted in Figure 4.5. Above 60% of the responses are in the agreement with the notion that same level networking in between module option supplier and support from the platform producers give the most effective of the innovative technology readily available. Responses to Q.19 provide an interesting insight as more than 60% of the responses agreed that MI would reduce the technological unpredictability by uniting various professional on a solitary platform.
Q. 20 to Q.29 were designed to obtain some practical insights and suggestions to make sure that it was not missed in earlier questions. To gain insights on the practical benefits of product design for MI in comparison with existing product design and customisation approaches, a descriptive question, Q.22 was included. Responses to this question provided insights on many aspects. Responses show that this new approach will give greater flexibility, speed, distinctness, the potential of serving to a new customer segment and product innovation in terms of the product offering. These responses were quite motivational as they provided many positive improvements which product design for MI might lead in traditional product design. Q.21 provided potential barriers to achieving the full innovation capabilities of this paradigm including complexity, dependence, and differentiation. Responses to Q.23 indicate that above 65 % of participants are in agreement with the notion that product design for MI will create new jobs along with more accessible products. Q.24 was designed to gain insights on intellectual property rights (IPR) in this product design approach. Responses to this question listed different perspective to handle IPR; it is difficult to forecast; it will depend upon who owns what. Building a specific organisation culture will be a challenge as players will constantly be changing. Responses to this question provide a basis for further investigation regarding IPR in MI.

Responses to Q.25 provided feedback on the potential practical impediments overlooked by the questionnaire survey. Lack of digital culture and training, unclear economic benefits and digital investments, lack of digital standards, norms and certifications, and unresolved questions around data security and data privacy are few issues which would need immediate attention for this approach to implement in the market. Q.27 was designed to obtain insights...
on the resources distribution strategy of a prospective firm who use both approaches, product design for MI and other traditional product design approaches. Responses to this question illustrate that 45% of the resources could be allocated to the MI. This shows the potential inclination towards MI by existing product design practitioner. Once the product design for MI is implemented in the market, this distribution share has the probability to increase.

Respondents to this survey also highlighted the acceptance of this new approach by senior leadership in organisations. This could be motivated by the lack of past research and market implementation which proves the significance of this approach. This inspires further investigation and development in the research area of product design for MI. Q. 28 was included in the survey to obtain insights on the potential consumer segment where this approach can be implemented and be fruitful. 39% of the respondents replied that the young and urban population could be an excellent point to start. An equal number of responses were in agreement with the notion that anyone can get benefit with this new and innovative product design approach.

To summarise, the survey questions addressing different vital aspects of MI helped to gain multi-dimensional insights on this approach. The majority of responses agreed with the notion that design for MI enhances creativity and innovation towards an individualised end product. However, at the same time, some responses were not in agreement with this notion. These responses provided the basis for further improvement in the approach.

Results discussed in this section are based on the limited sample size, given the scope of phase 2 of this thesis. As mentioned in section 3.3.2, to take part in the survey, 350 consumer product design companies were invited. Most of these invitations were sent to lead designers or experts associated directly with product design and development practices to obtain more realistic feedback on the approach, so for the given timeframe of phase 2 of this research, recorded responses yielded an adequate amount of valuable information about the innovative approach of product design for MI. These findings can be further verified with a larger sample size in future research.
4.3 INNOVATION TOOLKIT

Design of an innovation toolkit for OPAP has been approached in two different ways. In the first approach, individual models for end user, platform manufacturer and module options suppliers have been developed with individual optimisation model based on their pay-off functions. In the second approach, different design configurations have been modelled with a multi-level optimisation model. Both methods are explained in the following sections but only the second method has been selected for this research work.

4.3.1 Innovation toolkit based on game theory

The initial approach was to optimise the configuration of the OPAP with the consideration of one end-user, one platform manufacturer and multiple module suppliers using a three-move non-cooperative configuration game theory approach. The game approach allows to mimic the cooperation between different actors of MI. The end user takes the first move by taking the decision on platform and module option selection. The platform producer provides the platform with relevant constraints for the modules/interfaces. The concerned module options suppliers or 3rd party vendors make the last move to optimise their decisions including price discount and ordering policies. The ranges of rational reactions for the players are derived from the analyses of their pay-off models. These models represent an integrated configuration of OPAP. This kind of scheme is not only beneficial to end user but to all other players of the game.

For the end user, the objective function in the optimisation model is satisfaction index which is composed of cost and performance. For the platform producers, the objective function for optimisation would be the minimisation of development cost (DC) and sourcing cost (SC). Once the decision on the number of skeleton and number of interfaces has been finalised, DC can be calculated easily. SC is composed of unit purchase cost, ordering cost and material inventory holding cost.

Figure 4.6 illustrates the sequence of decisions taken by all the actors in the three moves dynamic configuration game. It is assumed that each supplier is homogenous with respect to the production of module options. The objective function for module options suppliers is to maximise their profit from the sale of module options. This profit can be seen as total revenue.
minus order processing cost, manufacturing setup cost, raw material ordering cost and module holding cost.

4.3.2 Innovation toolkit based on configuration modelling and multi-level optimisation

The design of the optimisation model for the innovation toolkit has been approached in four different steps: Modelling of OPAP; Modelling of evaluation measures and evaluation indices with end-user preferences; Identification of the optimal module options for every configuration; Configuration optimisation (Sikhwal & Childs, 2019). Based on the design of adaptable products (Martinez & Xue, 2017), a framework has been developed considering different design configurations, and for an overall satisfaction index for optimisation. Figure 4.7 depicts the framework for the innovation toolkit including the roles of different actors and the optimisation model.

The following assumptions are used for the development of the model:

1. The end-user acts as a lead to decide on the platform.
2. Adaptability and cost of the all feasible configurations with different module options are comparable.

3. The Primary requirement of the end-user can be represented by the module options of each module/interface, and it is only allowed to configure a product that offers higher-order module options than the customer requirements.

![Diagram](image)

**Figure 4.7 Framework for the Innovation toolkit**

The end product is a result of participation from platform producers, many module option suppliers and the end-user. This multi-directional participation causes many variations in the end product. These variations include two kinds of variation: variation of configuration in
terms of different interfaces used for modules and variation of module options for selected interfaces/modules. Different module options can be denoted by specific parameters. After selecting particular modules for skeleton interfaces, the second choice will be to select module options in terms of desired parameters for modules. So, a new method to model the variations of OPAP product configuration and the variations of product parameters in terms of module options is required.

4.4 MODELLING OF OPAP

Compared with traditional product customisation approaches, the variation of configuration and parameters is too high in product design for MI. Excessive variety might lead to problems in the design and manufacturing of products, so-called “mass confusion” (M. M. Tseng & Piller, 2003). Therefore, a sophisticated automated innovation toolkit is required for modelling of OPAP with variations. The end product is a result of participation from platform producers and many module option suppliers and the end user himself. This multi-directional participation causes so many variations in the end product. These variations include two kinds of variations: variation of configuration and variation of parameters. As the same type of module would be provided by different third-party vendors, the probability of variation of parameters is high. After selecting the OPAP skeleton from OEM, different module types will be selected by the end user. This will provide different configurations as per the end user’s choices. After selecting particular module types for skeleton interfaces, the second choice will be to select module options in terms of desired parameters for module types.

For automation of the modelling, the different product configurations are modelled by an AND-OR tree here. The product structure (OPAP skeleton) in OPAP can be decomposed into different sub-structures (module/interfaces), connected with an AND relation. Every sub-structure can be satisfied with different module options, and these module options are associated with an OR relation. Each module option in the AND-OR tree is further modelled in terms of parameters. These module options parameters include continuous parameters (e.g., dimensions of modules), integer parameters (e.g., a number of sub-module) and Boolean parameters (e.g., true or false for any particular module option).
Figure 4.8 shows the variations of an OPAP modelled by an AND-OR tree. The variations of configurations can be illustrated by combinations of different module options with different interfaces, selected by the end-user as per individual needs. A feasible individualised OPAP can be obtained from the AND-OR tree through a tree-based search (Russell & Norvig, 2002), described by a collection of Skeleton, Interfaces, and modules options nodes.

In this work, the following conditions are used to generate different feasible design configurations:

1. The first node should be the root node, to be selected.

2. After selecting the root node, all the sub-nodes should be selected, if all its sub-nodes are connected with an AND relation.

3. After selecting the root node, only one of the sub-nodes should be selected, if all its sub-nodes are connected with an OR relation.
A product configuration is characterised by a collection of modules arranged in a tree data structure. In this tree, the root node is the skeleton for the OPAP product which serves as the primitive in the design. Sub-nodes are used to model different modules which would interface with the skeleton or the root node. These module nodes are associated with the skeleton node (root node) with an AND relation. Other nodes, associated with the module nodes, are module options nodes. These module options nodes have an OR relation with modules nodes.

If a module node for the $i^{th}$ design configuration $S_i (i=1, 2, ...., n)$ is defined by $M_{ij} (j=1, 2, ... , m)$. This design configuration can be described as follows:

$$S_i = (M_{i1}, M_{i2} .... M_{in}) , \quad i = 1, 2, 3, .... n \quad (4.1)$$

A module node is associated with the different module options nodes. These module option nodes represent different design parameter choices for a particular module node. The $k^{th}$ design parameter $X_{ijk}$ of the module node $M_{ij}$ is defined in the form of $M_{ij}.X_{ijk}$. Therefore, the parameters of a module node, $M_{ij}$, can be described as follows:

$$X_{ij} = (M_{ij}.X_{ij1}, M_{ij}.X_{ij2} .... M_{ij}.X_{ijn}) , \quad i = 1, 2, 3, ... , n \quad \text{and} \quad j = 1, 2, 3, ... m \quad (4.2)$$

The parameters for the $i^{th}$ design configuration considering all involved nodes are defined by

$$X_i = (X_{i1}, X_{i2} .... X_{ik}) , \quad i = 1, 2, 3, .... n \quad (4.3)$$

The complete design solution of this configuration can be then defined,

$$D_i = (S_i, X_i) , \quad i = 1, 2, 3, .... n \quad (4.4)$$

If only $i^{th}$ design configuration is considered in terms of parameters, then

$$S_i = (X_{i1}, X_{i2} .... X_{in}) \quad (4.5)$$

### 4.4.1 Types of parameters for modelling

A product design configuration is further modelled by parameters. In this work, the parameters of an OPAP are classified into two categories: design parameters and non-design parameters (J. Zhang et al., 2015). This parameter defines specific add-on modules and unknown add-on modules. In this research, only parameters for specific module options are considered.
4.4.1.1 **Design parameters**

These are those parameters whose values need to be determined at the design stage. In this work, the design parameters are further classified into un-adaptable design parameters and adaptable design parameters.

- **Un-adaptable design parameters** are the parameters whose values are not changed in the product operation stage. For example, the width of a smartphone skeleton is an un-adaptable design parameter. In this work, the values of un-adaptable design parameters are achieved through optimisation.

- **Adaptable design parameters** are the parameters whose values need to be adapted at the product operation stage when requirements are changed. For example, the height of an office chair is an adaptable design parameter which can be adjusted for different persons.

4.4.1.2 **Non-design parameters**

These are those parameters whose values are provided as given conditions in design. For example, the mechanical properties of materials selected for the office chair are non-design parameters. Various constraints can also be further applied to these parameters. For an OPAP, since both the specific add-on modules and the unknown add-on modules need to be considered, the values of the adaptable design parameters are changed in two different ways during the product operation stage.

4.5 **MODELLING OF EVALUATION MEASURES AND EVALUATION INDICES WITH END-USER PREFERENCES**

OPAP provides different product configurations based on the individual requirements from the individual end-user. Different product configurations can be evaluated by different measures and indices.

4.5.1 **Evaluation Measures**

An evaluation measure is used to assess how well the given product configuration satisfies end-users’ requirements. It can either be a constant, a monotonic function of life cycle time.
(increasing or decreasing) or a non-monotonic function of life cycle time, as shown in Figure 4.9.

![Figure 4.9 Evaluation measure as (a) constant, (b) monotonic function, (c) non-monotonic function of life cycle time.]

For this research work, these measures can be classified into two categories: performance measures, $P_i$, and cost measures, $C_i$. Performance measures include efficiency, speed, resolution whereas cost measures include aspects such as product, module replacement and maintenance cost.

For a product configuration, $S$, with $n$ parameters, the evaluation measure in the $i^{th}$ evaluation aspect (measure) is defined by,

$$E_i = E_i(X_1, X_2, X_3, \ldots X_n)$$  \hspace{1cm} (4.6)

### 4.5.2 Evaluation Indices

Different evaluation measures are identified in specific units, so for further comparison, these evaluation measures are converted into comparable evaluation indices between 0 and 1, which represents different levels of satisfaction (Yang, Xue, & Tu, 2005). Customer (End-user) satisfaction has been selected as an evaluation index for this thesis. Different comparable evaluation indices can be integrated to model the overall customer satisfaction index.

### 4.5.3 Conversion of Evaluation Measures into Evaluation Indices

The evaluation measure and evaluation index can be related by a linear or a nonlinear function. The evaluation measures can be classified into three categories: the-smaller-the-better, the-larger-the-better, and the-nominal-the-best (Martinez & Xue, 2017). However, in
the case of an evaluation index, the higher evaluation index represents a higher satisfaction level.

The customer satisfaction index, in the $i^{th}$ evaluation aspect, is defined by,

$$CS_i(X) = F_i[E_i(X)]$$

where $i = 1, 2, 3\ldots m$

After converting all the customer satisfaction indices into comparable measures, these $m$ indices can be described by values in between 0 and 1. By considering the importance of these evaluation measures, overall customer satisfaction index, $CS$, can be modelled as follows:

$$CS(X) = \frac{1}{W_1 + W_2 + W_3 + \ldots + W_m}[W_1CS_1(X) + W_2CS_2(X) + W_3CS_3(X)$$

$$+ \ldots + W_mCS_m(X)]$$

(4.8)

where $W_1, W_2, \ldots, W_m$ are $m$ weighting factors for $m$ evaluation indices, selected by end-users, according to their individual requirements and preferences.

These individual weighing factors are selected by the end-users according to their individual requirements and preferences. Other methods to identify the weighing factors of different evaluation measures have also been developed in the literature. One such method is the pairwise comparison method developed by Saaty (1980). The relation between an evaluation measure, $E_i(X)$ and its evaluation index, $CS_i(X)$, could be in the form of discrete points or a continuous function. If in the form of discrete points, then this relationship needs to be converted into a continuous function relation as a continuous function is required for optimisation. The continuous function from discrete points is identified by the least-square curve-fitting method (Hoffman, 2001). If the relationship between an evaluation measure, $E_i(X)$ and its evaluation index, $CS_i(X)$, is specified by a quadratic polynomial, then it can be defined as follows:

$$CS_i(X) = a_{0i} + a_{1i}E_i(X) + a_{2i}E_i^2(X)$$

(4.9)

where $i = 1, 2, 3\ldots m$

$a_{0i}, a_{1i}$ and $a_{2i}$ are the three coefficient of the quadratic polynomial function.
When values of $E_i(X)$ and $CS_i(X)$ are given in numbers, these coefficients can be obtained using the least-square curve-fitting method.

![Figure 4.10 Least-square curve-fitting method](image)

When the evaluation measures are modelled by discrete values, the non-linear relation is described by discrete points on $E_i(X)$ - $CS_i(X)$ graph, shown in Figure 4.10. Evaluation measures modelled by integers and Boolean values of true and false are treated as special cases of discrete evaluation measures (Hong et al., 2008). In the case of Boolean value, the relationship between $E_i(X)$ and $CS_i(X)$ are described by two points in the $E_i(X)$ - $CS_i(X)$ graph.

### 4.6 Identification of the Optimal OPAP Configuration with Optimal Module Options

Since a large number of design configuration with different module options can be selected to fulfil the individualised requirement, a multi-level optimisation is employed to identify the best design configuration with optimal module options. A multilevel optimization model is employed in this work to identify the best design configuration and its design parameter values. In this optimization model, first the optimal design parameter values for the $i^{th}$ design configuration are achieved through parameter optimization.

Configuration optimisation is to be undertaken to achieve the $i^{th}$ configuration, which optimises the satisfaction of the end user requirements. The same toolkits can be expanded and customised for other actors such as smaller companies. This can be summarised as follows:

**Objective function:** To find the $i^{th}$ design configuration with optimised module options.
To optimise: Satisfaction of the end-user requirements will be maximised from the design configuration within the constraints provided by other actors of the OPAP ecosystem. Specific parameters will be defined to measure the end-users satisfaction from the given design configuration.

Constraints: A large manufacturer, responsible for the manufacturing of the platform and interfaces, may define some constraints including functional, safety and assembly constraints. Smaller companies providing the module options may also provide some constraints based on their manufacturing capability, spatial constraints and other constraints.

After evaluating different platform-module options configurations by an overall customer satisfaction index, these configurations can be optimised by this multi-level optimisation model. The overall customer satisfaction index can be considered as the optimisation objective function. The average-case in which the average evaluation index is used as the objective function method is generally the most suitable for the optimal design of OPAP. The same innovation Toolkit can be expanded and customised for other actors such as smaller companies. The optimisation is conducted at two levels: the module options level and the configuration level.

A feasible configuration, defined by its parameters, can be represented as follows:

\[ S_i = (X_{i1}, X_{i2}, \ldots, X_{in_i}) \]  

The first level of optimisation is conducted at the parameters level, i.e. selection of optimised modules in the same kind of module options. The optimal module options considering one product configuration is obtained by following the optimisation model:

Find : parameters \( X_i \)

To Optimise:

\[ \text{Max} \quad \text{wrt} \quad X_{i1}, X_{i2}, \ldots, X_{in_i} \quad CS(X_{i1}, X_{i2}, \ldots, X_{in_i}) \]

Subject to:

\[ X^{(L)}_i \leq X_i \leq X^{(U)}_i, \quad i = 1, 2, 3, \ldots, n \]  

\[ h_i(X_i) = 0, \quad i = 1, 2, 3, \ldots, n \]
\[ g_i(X_i) = 0, \quad i = 1, 2, 3, \ldots, n \] (4.14)

where CS is the overall customer satisfaction index, and \( X^{(L)}_i \) and \( X^{(U)}_i \) represent the lower boundaries and upper boundaries of \( X_i \) respectively.

The second level of optimisation is conducted at the configuration level, i.e. selection of optimised OPAP configuration for the end product. Among all the \( p \) feasible product design configuration solution candidates, the optimal design solution is obtained through configuration optimization. The optimal configuration is identified from all the feasible configuration by following the optimisation model:

**Find:** the \( i^{th} \) design configuration candidate

**To optimise:**

\[
\text{Max}_{\text{wrt } S_i^*} \ CS(S_i^*) \tag{4.15}
\]

**Subject to**

\[ 1 \leq i \leq p \tag{4.26} \]

where \( S_i^* \) is iterated among the feasible configurations with the optimised module options, \( i \) represents the \( i^{th} \) design configuration candidate, and \( p \) is the number of all feasible design configuration candidates.

One potential approach for this second level optimisation to obtain the optimised configuration of the end product is Pareto Analysis. This analysis is used to select a number of most effective actions that satisfy the given requirements. Pareto analysis has also been used to determine the Pareto-design solutions for a given module set (Rai & Allada, 2010). However, Pareto analysis treats all the faults or fitness equal and excludes possibly important configurations which are small in fitness measure.

In this work, genetic programming (Koza, 1992) is used for configuration optimisation, and penalty-based optimisation (Arora, 2017) is used for parameter optimisation.
4.6.1 Module Option Optimisation

The first level of optimisation is conducted at the module options level, i.e., selection of optimised module options into chosen interfaces, for a given configuration. In this work, module option optimisation is done with penalty-based optimisation (Arora, 2017) method. Different actors provide different constraints according to their preferences. In the presence of these constraints, penalty-based optimisation is used to convert a constrained optimisation problem into an unconstrained optimisation problem. Penalty based optimisation models use a penalty function for this conversion. The optimisation objective functions in the parameter optimisation can be defined by any of the following three methods (Martinez & Xue, 2016):

1. The average-case method
2. The best-case method
3. The worst-case method

In the average-case approach, the average evaluation index is employed as the objective function for parameter optimisation considering one feasible design configuration. The average-case method can be the most suitable for the optimal design of OPAP. The best-case method is used when the maximum evaluation measure during the product utilisation span is expected, e.g. maximum speed for a racing car. The worst-case method is used when the minimum evaluation measure during the product utilisation span is considered, e.g. design for the lowest risk of failure for hair styling tongs.

Module options optimisation provides a fitness measure for a particular end product configuration by calculating the best overall customer satisfaction index. The objective function evaluation index obtained by this optimisation is selected as the evaluation index for that particular product configuration.

The optimal parameter values for a product configuration, $S_i$, defined by its parameters $(X_{i1}, X_{i2}, \ldots, X_{in})$, using a constrained optimisation approach, can be obtained as follows:

$$
\text{Max}_{\text{wrt } X_{i1}, X_{i2}, \ldots, X_{in}} \text{CS}(X_{i1}, X_{i2}, \ldots, X_{in})
$$

(4.17)

Subject to:
\[
X_{ij}^L \leq X_{ij} \leq X_{ij}^U, \quad j = 1, 2, 3, \ldots, n_i \\
\]

(4.18)

\[
h_{ij}(X_{i1}, X_{i2}, \ldots, X_{in_i}) = 0, \quad j = 1, 2, 3, \ldots, k_i \\
\]

(4.19)

\[
g_{ij}(X_{i1}, X_{i2}, \ldots, X_{in_i}) = 0, \quad j = k_i + 1, k_i + 2, \ldots, m_i \\
\]

(4.20)

Adding a penalty term to the objective function mentioned in equation 4.17 will convert this constrained optimisation problem into a non-constrained optimisation problem. The modified objective function with a penalty term can be defined as follows:

\[
UCS_i(X_{i1}, X_{i2}, \ldots, X_{in_i}) = CS_i(X_{i1}, X_{i2}, \ldots, X_{in_i}) - \varphi \cdot p_i(X_{i1}, X_{i2}, \ldots, X_{in_i}) \\
\]

(4.21)

where, \(UCS_i\) represents the non-constrained form of \(CS_i\), \(p_i(X_{i1}, X_{i2}, \ldots, X_{in_i})\) is the penalty term for the unconstrained objective function and \(\varphi\) is a multiplier constant that determines the magnitude of the penalty.

The penalty term is defined as follows:

\[
p_i(X_{i1}, X_{i2}, \ldots, X_{in_i}) = \sum_{j=1}^{k_i} [h_{ij}(X_{i1}, X_{i2}, \ldots, X_{in_i})]^2 + \sum_{j=k_i+1}^{m_i} [g_{ij}(X_{i1}, X_{i2}, \ldots, X_{in_i})]^2 \\
\]

(4.22)

4.6.2 Configuration Optimisation

The second level of optimisation is conducted at the configuration level, i.e. selection of optimised OPAP configuration for the end product. The following optimisation model is used:

\[
\max_{\text{wrt } S_i^*} CS(S_i^*) \\
\]

(4.23)

Subject to:

\[
1 \leq i \leq p \\
\]

(4.24)

Where \(S_i^*\) is obtained by iteration among the feasible configurations with the optimised module options, \(i\) represents the \(i^{th}\) design configuration candidate, and \(p\) is the number of all feasible design configurations.

Genetic programming (Koza, 1992) is used here for configuration optimisation. Genetic programming is based on genetic algorithms, and can be used to solve an optimisation
problem with solutions modelled by tree data structures (Michalewicz, 1996). Genetic algorithms are stochastic optimization methods utilise the concepts of natural selection and genetics (Goldberg & Holland, 1988; Holland, 1975). These algorithms use a population of individuals, each representing a possible solution to a given problem. Those individuals are generated and evaluated iteratively using an evaluation function. Genetic algorithms have been applied to various set of problems in diverse fields such as engineering, management, operations research.

In genetic programming, multiple solutions are considered in the population of a generation. These solutions are called chromosomes which evolves with better evaluation measures through three operations: reproduction, crossover and mutation. The chromosomes with comparatively poor evaluation measures may become extinct in the evolution process until the solutions cannot be improved further. The better evaluation measures chromosomes play a more dominant role in the reproduction process, so the evaluation measure of the new generation is always improved that in the last generation.

The genetic programming used in this work is inspired by the work done by Hong et al. (2008), and is outlined in the following steps:

1. Create the first generation with \( n \) feasible end product configuration. Each individual configuration is generated randomly from the configuration AND-OR tree structure.

2. Obtain the overall customer satisfaction index of each individual configuration in the current generation with optimal module options from first level optimisation. This represents the fitness of the corresponding individual configuration.

3. Create a new generation from the current generation by repeating the process of reproduction, crossover and mutation until the number of design configurations in the new generation reaches \( n \). This new generation becomes the current generation for next evolution process step.

4. The evolution process should be stopped when the average fitness of a generation cannot be significantly enhanced in the last \( m \) generations or the pre-defined maximum generations, \( g_{\text{max}} \), has been reached. The improvement in generations is pre-defined. For a generation to
be considered as the next generation of the evolution process, the difference in the overall customer satisfaction indices should be more than this pre-defined value.

5. The best individual configuration in the latest generation is selected as the optimal end product configuration.

4.6.2.1 Reproduction

In the reproduction, two parents based on their fitness using the roulette wheel selection method, from the current generation are selected. The size of the section in the roulette wheel is proportional to the fitness of the individual. This means that the chances of getting selected are higher for the individual who has higher fitness or evaluation index. To select the individual, a marble is tossed in the roulette wheel, and the individual is chosen where the marble stops. The roulette wheel selection method, formulated by Hong et al. (2008) is employed in this research. This selection is continued until the number of individual configurations in the new generation reaches the number of the population.

This roulette wheel selection method is formulated as follows:

1. Calculate the sum, $A$, of the fitness measures, $f_i$, for all individuals in the population.

2. Generate a random number, $r$, from the interval $(0, A)$.

3. Go through the individuals in the population and obtain the sums of the fitness measures from the first individual to the $i^{th}$ individual. The $i^{th}$ individual is selected for reproduction when the sums satisfy the condition:

$$\sum_{j=1}^{i-1} f_j < r < \sum_{j=1}^{i} f_j$$

(4.25)

This selection is continued until the number of individuals in the new generation reaches the number of the population.

4.6.2.2 Crossover

Two sub-trees are swapped from two different parent individuals in the crossover operation. To swap sub-trees, two different positions are selected as the root nodes of the sub-trees. A small cross-over probability, threshold cross-over probability $p_c^{(t)}$, is defined to avoid significant random changes of the individual in the next generations. When a created cross-
over random number $p_c$, is higher than this probability than the cross-over operation is conducted. To enhance the efficiency of genetic programming, an adaptive method to get the cross-over probability has been developed by Srinivas and Patnaik (1994). In this method cross-over probability, $p_c$, is calculated as follow:

$$p_c = \begin{cases} \frac{f_{\text{max}} - f_{\text{bigger}}}{f_{\text{max}} - f_{\text{ave}}}, & f_{\text{bigger}} \geq f_{\text{ave}} \\ 1, & f_{\text{bigger}} < f_{\text{ave}} \end{cases}$$

(4.26)

where $f_{\text{max}}$ is the maximum fitness measure in the population, $f_{\text{bigger}}$ is the larger fitness measure in one of the two selected parent individuals, and $f_{\text{ave}}$ is the average fitness measure for all the individuals in the population.

When each node is associated with a positive integer, the position of crossover is identified by:

$$L_c = \text{int}[(n - 1)P_c + 1]$$

(4.27)

where $n$ is the number of nodes in the individual, and $P_c$ is a random number between 0 and 1.

For the crossover position, the following conditions should be satisfied:

1. The node at the selected location should not be a root node in the AND-OR tree.
2. The two nodes at the selected two locations of the parent individuals for a crossover should have an OR relation.

4.6.2.3 Mutation

After the cross-over phase is completed, the mutation operation is applied to each of the two parent configurations. A mutation position is selected in the configuration with an OR relation randomly, and that subtree is removed from the configuration. This is replaced by a new subtree which has OR relation with the previously selected individual. A small mutation probability, threshold mutation probability $p_m^{(t)}$, is defined to avoid significant random changes of the individual in the next generations. When a created mutation random number $p_m$ is higher than this probability then the cross-over operation is conducted. To improve the efficiency of genetic programming, an adaptive method to obtain the mutation probability is
developed by Srinivas and Patnaik (1994). In this method mutation probability, \( p_m \), is calculated as follow:

\[
    p_m = \begin{cases} 
        0.5 - \frac{f_{\text{max}} - f}{f_{\text{max}} - f_{\text{ave}}}, & f \geq f_{\text{ave}} \\
        0.5, & f < f_{\text{ave}} 
    \end{cases}
\]  

(4.28)

where \( f_{\text{max}} \) is the maximum fitness measure in the population, \( f \) is the larger fitness measure in one of the two selected parent individuals, and \( f_{\text{ave}} \) is the average fitness measure for all the individuals in the population.

When each node is associated with a positive integer, the position of crossover is identified by:

\[
    L_m = \text{int}[(n - 1)p_m + 1]
\]  

(4.29)

where \( n \) is the number of nodes in the individual, and \( p_m \) is a random number between 0 and 1.

For the crossover position, the following conditions should be satisfied:

1. The node at the selected location should not be a root node in the AND-OR tree.

2. The node at the selected location should have an OR relation with other nodes in the AND-OR tree.

### 4.7 Case Studies Implications

The concept of product design for MI can be implemented in the market with a variety of products, but earlier study suggests that consumer electronics and furniture industries would be suitable as a possible starting point. This was inspired by the fact that it is easy to adapt OPAP in these industries, both by end-users and module options suppliers. Following this direction, a consumer electronics product, OPAP Smartphone (based on Google ARA) and an individualised chair (based on Axia Smart Chair from Nomique) are used as case studies.
4.7.1 An OPAP Smartphone (Google ARA)

Project Ara is the code name for a Google’s project that has been started to develop an open platform hardware for creating modular smartphones (Ray, 2015). The open platform includes a structural frame or endoskeleton that connects and holds modules as per the customer's choice, such as a display, battery, camera or speakers. Users can have many variants according to the integration of the modules in the platform. This would allow users to upgrade individual modules as advanced modules emerge or remove non-working modules and replace with a new one. This will provide longer lifetime cycles for the handset, and will reduce electronic waste. Figure 4.11 shows Google ARA with different modules.

![Google ARA with different modules](image)

*Figure 4.11 Google ARA, A smartphone based on OPAP (Project ARA by Google 2016)*

This project was started by the Advanced Technology and Projects team within Motorola Mobility when it was a subsidiary of Google. Google has divested Motorola to Lenovo, but it retained the Advanced Technology and Projects group. Since then it is working under the direction of the Android division (Patel, 2014). A smartphone from Project Ara was scheduled to begin a pilot testing in the USA in 2016 with a target cost of $50 for a basic grey phone (Gannes, 2014). But later in the same year, Google announced that the Ara pilot in Puerto Rico is delayed indefinitely. Pensworth (2019) from Daily wireless explains few probable reasons for this delay in launching the project ARA in the market. These reasons include a lack
of support from the existing ecosystem of smartphones and lack of technology in terms of connecting different module options on the skeleton.

This case study is relevant to this work as the design principles behind Project Ara are similar to the approach of this research. However, in this case study, the end product is mainly designed and manufactured by the companies which are in direct contact with the OEM, i.e. Google. The user has no role during the design and development phase of the platform and other modules. Options will be available to the customer as it is in the product design for MC.

Figure 4.12 Google ARA detailed development

This case study can be used to test the framework which will be developed in this research and feedback from this can be extended to other types of products. Figure 4.12 shows the descriptive development of ARA.

Information available in the public domain for ARA has been used to formulate the optimisation problem for an OPAP smartphone. Information is gathered from the Modular development kit (MDK), a guide for the development of modular technology that Google has provided to developers (Project ARA by Google, 2016).

Due to variations of OPAP, selected products are not the optimised one with optimal modules. Once the end-user puts forward the choice for the required module type (e.g., battery module, camera module), different smaller companies will provide different module options
(e.g., different capacities for battery, different resolutions for the camera). The variations of this smartphone with different potential module options for four selected modules are shown in Figure 4.13. As the energy requirement for a higher resolution camera module option will be higher than one with a lower resolution, the battery usage, for an OPAP smartphone with the higher resolution camera module option, will be higher than for an OPAP smartphone with the lower resolution camera module option. For every feasible product configuration, these relations will vary. Hence, the innovation toolkit will be employed to find the end product which provides a smartphone with optimal module options for the given requirements.

![Diagram of product configuration options](image)

**Figure 4.13 Two different feasible configurations based upon interfaces selected by end-users**

Two different feasible configurations (Figure 4.13) based upon the type of modules selected by end-users can be denoted as follows:

\[
S_1 = \text{(Camera Module, Battery Module, Screen Module)} \quad \text{(4.30)} \\
S_2 = \text{(Speaker Module, Battery Module, Screen Module)} \quad \text{(4.31)}
\]

Different feasible product configurations (not with optimal module options) can be created from the AND-OR tree configuration shown in Figure 4.13 (a). Figure 4.14 illustrates two of such sub-configurations.

From the configuration \(S_1\), different sub-configurations, \(X_1\) and \(X_2\) can be obtained with different module options:
\[ X_1 = (10MP, 1600mA \text{ h, AMOLED}) \] (4.32)
\[ X_2 = (12MP, 1800mA \text{ h, LED}) \] (4.33)

**Figure 4.14** (a) OPAP smartphone configuration, S1 (b) Feasible product sub-configurations

Table 4.5 shows different customer evaluation measures selected for this case study. Product cost, \( C_p \), is selected as the cost evaluation measure and, weight, \( P_w \), and battery backup, \( P_{bb} \), have been selected as performance evaluation measures. The product cost for different configurations can be determined based on individual cost from different module options suppliers. For weight and battery backup, different correlations in terms of parameters are used. These three evaluation measures \( C_p \), \( P_w \) and \( P_{bb} \) are converted into three customer satisfaction indices, \( I_p \), \( I_w \) and \( I_{bb} \), respectively.

**Table 4.5 Customer evaluation measures selected for OPAP smartphone**

<table>
<thead>
<tr>
<th>Evaluation measures</th>
<th>Unit</th>
<th>Representation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost evaluation measure</td>
<td>Product Cost</td>
<td>GBP (£) ( C_p )</td>
</tr>
<tr>
<td>Performance evaluation measure</td>
<td>Product Weight</td>
<td>Grams (g) ( P_w )</td>
</tr>
<tr>
<td></td>
<td>Battery backup</td>
<td>Hours ( P_{bb} )</td>
</tr>
</tbody>
</table>

If the weighting factors provided by end-users are \( x_1 \), \( x_2 \), and \( x_3 \) then the overall customer satisfaction index,
\[ CS(X) = \frac{1}{x_1+x_2+x_3} \left[ x_1I_p + x_2I_w + x_3I_{bb} \right] \] (4.34)

This equation will be used for the optimisation of the customer satisfaction index with optimal module options’ parameters as per equation 4.17. The configuration satisfying these parameter values gives the best possible candidate for the highly individualised end product. Once both configurations are with optimal module options, a genetic algorithm is employed to obtain a highly individualised and an optimal OPAP smartphone.

The end product obtained by this method will have a different configuration for different values of weighting factors for customer satisfaction index, selected by different end-users. In this case study, the number of variations of OPAP is limited to demonstrate the approach. For a more significant number of variations, automated innovation toolkit can be used. This case study shows that innovation toolkit developed in this thesis will be able to provide a more individualised smartphone, exactly tailored to the needs of every end-user.

4.7.1.1 Reflections on market failure of this case study product, in connection with survey output

Google ARA intended to provide the end-user with an individualised end product, exactly tailored to the needs of every user. But this product could not be implemented in the market in the first scheduled launch. As mentioned in chapter 2, the idea of open platform architecture product is relatively recent and in the absence of any existing application, this approach needs more consideration before implementing in the market. Findings from the first phase of this research, in particular, responses to Q. 21 and Q.25 of the survey can provide some reflection on the failure of this case study product in market.

As pointed out in the response of Q.25, organisational culture in terms of existing eco-system of smartphones could be one of the barriers in successful implementation. Project ARA would affect the whole smartphone industry at many frontiers. There would be hesitation in accepting the idea of an open platform by big established smartphone companies so lack of support from existing organisation culture could be one of the key reasons for the failure of this case study product. Response to Q.21 also pointed out that with OPAP, it would be difficult for manufacturers to differentiate their products from competitors. As noted in
responses to Q.21, the inertia to adopt this new paradigm, IP protection, information management could be other reasons for the lack of due support to ARA.

4.7.2 An Individualised Chair (Axia Smart Chair by Nomique)

The innovation toolkit, which is used to obtain an individualised smartphone in case study 1, can be implemented for other individualised end products. Another product, the Axia smart chair from Nomique was selected as a case study to demonstrate the application of the OPAP and the innovation toolkit. This chair is designed to provide a healthier posture and have a modular system for cushions. Figure 4.15 shows the Axia smart chair with different module options for cushions.

[Image: An individualised chair (Axia Smart Chair by Nomique 2018)]

OPAP with the innovation toolkit can be used for this kind of smart chair. One large manufacturer can provide the skeleton with a smart seating system, and other module options (components or set of components) will be provided by various smaller companies. Once the end-user puts forward the choice for the required module type (e.g., armrest, base), different smaller companies will provide different module options (e.g., different shape and comfort for armrests, a different kind of bases). The variations of OPAP chair with different potential module options can be configured in an AND-OR tree diagram as done for last case study in Figure 4.13.
Due to the significant variation in module options, selected products are not the optimised one with optimal modules. Different evaluation measures, e.g., chair cost, chair weight were selected for this case study and converted into respective evaluation indices to get the overall customer satisfaction index for the first level of optimisation (for optimal module options). The second level optimisation is then employed to obtain an optimised and highly individualised smart chair. This case study is presented briefly in this chapter to demonstrate the effectiveness of the introduced innovation toolkit in a range of products and the arising configuration are illustrated in Figure 4.16.

![Figure 4.16 (a) OPAP smart chair configuration (b) Feasible product sub-configurations.](image)

**4.7.3 Additional examples**

As the earlier study suggests, this framework can be used in the range of products. While the case studies investigated in the previous section are within the context of two specific markets, these reflections on the applicability of developed toolkit are generalisable to industrial products of similar product architecture, complexity and comparable level of end-user involvements. OPAP with introduced innovation toolkit can be used to obtain highly individualised and optimised end products for these markets. Table 4.6 summarises a few other potential case studies where the devised framework could be implemented.
### Table 4.6 Potential case studies

<table>
<thead>
<tr>
<th>OPAP</th>
<th>Evaluation Measures</th>
<th>Evaluation Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>BLOCKS (Blocks, 2018)</td>
<td>Cost, Weight, Size, Battery Backup, Performance (response time)</td>
<td>Customer Satisfaction Index</td>
</tr>
<tr>
<td>Fonkraft (Fonkraft, 2018)</td>
<td>Battery backup, Cost, Weight, Size, Performance (response time)</td>
<td>Customer Satisfaction Index</td>
</tr>
<tr>
<td>PuzzlePhone (PuzzlePhone, 2018)</td>
<td>Battery backup, Cost, Weight, Size, Performance (response time)</td>
<td>Customer Satisfaction Index</td>
</tr>
</tbody>
</table>
To summarise, this chapter highlights and discusses various research findings along with the discussion. This chapter identifies key areas which need to be focused on to realise the innovative approach of MI with OPAP and convert it into an industrial practice by an explorative study of existing product design and customisation approaches. The findings of industrial questionnaire show that the end product from product design for MI will be more creative and innovative, and offers more individualised and technologically advanced products. This chapter also describes the developed framework for the Innovation toolkit for the end-user. The innovation toolkit uses a multi-level optimisation model to identify the optimal design configuration for OPAP to satisfy the exact needs of the end-users. The innovation toolkit is applied to two product platforms to illustrate the applicability of the proposed innovation toolkit. These case studies show that the developed innovation toolkit for Design for MI with OPAP will help end user to obtain optimised and highly individualised end product. These case studies are presented briefly in this chapter to demonstrate the effectiveness of the introduced innovation toolkit. The following chapter investigates and presents another case study OPAP product in more details.
5 CASE STUDY

CASE STUDY 1: BLOCKS

BLOCKS is a modular smartwatch company with OPAP design approach. It is a start-up born and bred in London. A BLOCKS smartwatch has two parts: The Core and the Strap. The idea of the core is similar to the idea of Platform in this study. The strap is made of several customer selected modules known as blocks. Customers can choose the modules which best suit their lifestyle and needs. Different blocks (modules) with a specific functionality are added to the core (platform) to individualise the final smartwatch. Blocks can be exchanged for new applications as and when needed. Figure 5.1 illustrated BLOCK along with some of its module options.

As the emphasis of this research is on the use of innovation toolkit to obtain the optimal OPAP, this case study product provides with the opportunity to implement this innovation toolkit in the absence of any other complete existing market application. This could also be useful to understand the interaction between user and product in the design phase as a combination of different modules, interfaces and, platform. The case study is investigated on the parametric level to illustrate the effectiveness of the innovation toolkit. An interview was
designed, and interview results are used as a means of obtaining insights for this case study product exploration.

5.1 INSIGHTS FROM INTERVIEW ON BLOCKS

The first part of the interview was designed to capture insights necessary to form an overall understanding of the product design for MI with OPAP, from experts actively involved with this kind of products in the market. The core idea of MI is to provide individualised end products and networked innovation in product design. Current developments such as Industry 4.0, Innovation 4.0, IoT, and increasing user aspiration for individualised products are further strengthening this approach. The interview results provide knowledge of experts associated with MI with OPAP. This part of the interview results also provides an overview of best practice, potential barriers and suggestions for improvements. These results also provide insights into the background and motives of MI practitioners. All interview results along with questions are summarised in Appendix C.

Response to Q.1 provides insights on the positioning of BLOCKS in MI space. These responses form the basis of using an open platform architecture to address enhanced user aspirations of choice of selecting more than one feature in a traditional product. BLOCKS was first aimed to satisfy the need of gesture control and health monitoring device in a smartwatch with the option of choosing a different application. Modularity or open platform architecture paved the way to provide this offering to customers or end-users. Response to Q.2 summarises the main success factor behind the success of BLOCKS. Targeting the right market and the right set of customers was one of the key factors which contributed to the success of the BLOCKS. This feedback is in line with the earlier finding of this research, as the first phase of this research also identified that consumer electronics would be a most suitable market to implement MI with OPAP because customers in this segment are more aware and readier to actively involved in the product design and development process.

Response to Q.3 resonates with the key enablers of MI with OPAP identified in this thesis. This response summarises rapid prototyping, open innovation, incoming of IoT and 3D printers, and inclination towards individualisation as some factors which opens up the door for the idea of MI. Importance of a suitable market and appropriate customer segments is
also iterated as a factor affecting the product individualisation. Q.4 was an addition to the previous questions as it was designed to know about trends responsible for the motivation for the introduction of MI in the market. Besides technological advancement, awareness about the need for more sustainable products, benefits of upgradable products, are some of the trends which are influencing the business of OPAP products most. This influence is mostly positive and encouraging the further development and implementation of this approach in the market with a variety of products.

As this research identifies the suitability of consumer electronics product market for the implementation of MI with OPAP, Q.5 was designed to gain some insights on future pathways of these products from OPAP practitioners. This response sees MI as a key contributor to the circular economy which is need of the hour. This response also finds OPAP as a successful alternative to planned obsolescence from present-day companies which aims to provide new and advanced features to customer every next year. MI with OPAP will be able to provide new products as the end-user can easily swap the old module options with new and advanced module options. Response to Q.6 talks about core factors in the configuration process of open platform architecture products. This response puts light on the role of involvement of multiple actors for the design and development of an OPAP end product. This response presents two alternatives to this approach. In the first situation, if one company can provide multiple types of modules than there is no requirement for many module option suppliers. In the second situation, multiple vendors or module option suppliers can come together to provide a different module for the end product. However, the second situation depends upon the availability of the required vendors. The framework of the MI ecosystem devised in this research considers the second situation as current connectivity means and platforms had brought together vendors from across the globes much closer than ever before.

Q.7 is designed to know about potential barriers to opening up the product design and development process with OPAP, with BLOCKS as an existing application of this approach in the market. Cost efficiency is mentioned as one of the key challenges for this kind of product. This is an important insight as this encourages to focus more on the monetary aspects and economies of MI with OPAP before implementing this approach in the market on a larger scale.
Responses to Q.8 and Q.9 highlights the success factors and future of companies which would use MI with OPAP as their product design and development strategies. These responses are quite encouraging for this research as it is mentioned that there is definite space for this kind of product in the market. Given the benefits MI provides at multiple frontiers, this approach will encourage many actors to participate actively and produce an individualised and sustainable end product. This approach could be a cost-effective solution to the needs of today’s market. Also, this approach will help in terms of educating customers about the end product they are selecting to buy. Q.10 was designed to obtain some insights regarding questions which are yet to be addressed in the domain of MI with OPAP. Responses to this question stress the need to identify the point where individualisation needed to be inserted in the market. This response also summarises the importance of more research in terms of background, in terms of the policy making and income factors. The responses also mentioned that another research approach to further the area of MI with OPAP is just to make a product and launch in the market and then see the pattern. Coming from a partition dealing with OPAP in the market, this response is quite useful as weighs the idea of prototyping of an OPAP product and test in the market to obtain more insights on this approach.

Response to Q.11 provides advice on current research on MI with OPAP as a key enabler. This response provides advice to work very closely with companies or entities that are working with this kind of products and see the real world impact of these products. This response also put emphasis on the engagement with the end-user and how feedback form the end-user engagement can provide new insights which were never thought of. The last question was designed to obtain advice to an ambitious entrepreneur who wants to work with this kind of products. Response to this question highlights the importance of market feedback in terms of the success or failure of the product designed and developed with this approach.

In summary, the first part of the interview provides insights at multiple fronts, ranging from the current situation in the market of OPAP products to advice on future pathways and research needed to further this approach. These interview responses iterate the importance of end-users in the success of MI with OPAP.

The second part of the interview was designed to obtain, and cross-verify types of module options offered and associated parametric details of the BLOCKS. These details were
presented to interviewee (founder of BLOCKS) in such a manner that these details can be used to model the OPAP. Presented details were obtained from the information available on the website of BLOCKS. Following the cross-verification with the interviewee, some further parametric details of various module options types were added to suit them for the modelling for the multi-level optimisation model of the innovation toolkit. Different module option along with their characteristics are shown in Table 5.1.

<table>
<thead>
<tr>
<th>Module</th>
<th>Module options</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Environmental Sensor</td>
<td>1. Temperature</td>
<td>A localised environment data sensor used to monitor temperature, air pressure and humidity for information related to incoming weather changes</td>
</tr>
<tr>
<td></td>
<td>2. Temperature with Air Pressure,</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3. Temperature with Air Pressure and Humidity</td>
<td></td>
</tr>
<tr>
<td>Heart Rate Monitor</td>
<td>1. Intermittent Heart Rate Monitor</td>
<td>This module can be plugged to measure your pulse. This can be used wither by taking readings over intervals or tracking heart rate throughout the workout to optimise the training.</td>
</tr>
<tr>
<td></td>
<td>2. Continuous Heart Rate Monitor</td>
<td></td>
</tr>
<tr>
<td>LED</td>
<td>1. Low power LED</td>
<td>This module is a handy adjustable LED flashlight with strong lighting and notification features. This can help to enhance the visibility in transit at night, also to find the way in the dark.</td>
</tr>
<tr>
<td></td>
<td>2. High power LED</td>
<td></td>
</tr>
<tr>
<td>Smart Button</td>
<td>1. Touch activated</td>
<td>This module is activated by a touch sensor or voice activation and can launch a range of connected apps or commands.</td>
</tr>
<tr>
<td></td>
<td>2. Voice activated</td>
<td></td>
</tr>
<tr>
<td>GPS</td>
<td>1. GPS receiver</td>
<td>This module type is a high sensitivity GPS and GLONASS receiver that provides location data to help in tracking speed, tracking journey and navigate easily.</td>
</tr>
<tr>
<td></td>
<td>2. GLONASS receiver</td>
<td></td>
</tr>
<tr>
<td>Extra Battery</td>
<td>1.95 mA h</td>
<td>This module can be connected on the strap to charge the battery of the Smartwatch. Each new module is increment equivalent to 95 mA h or 25% of additional charge.</td>
</tr>
<tr>
<td></td>
<td>2.190 mA h</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3.285 mA h</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4.380 mA h</td>
<td></td>
</tr>
</tbody>
</table>
Table 5.1 shows different types of module available for end-users to integrate on the strap (platform). All the modules shown in this table are taken from Phase 1 of BLOCKS module development process. Various parametric details are obtained either by BLOCKS product catalogue or from the interviewee. These modules include different types of environmental sensors, heart rate monitors, LED lights, smart button, GPS and extra battery. Different module options to these modules are also shown in this table. For BLOCKS, these module options are invented and produced by themselves, but in the framework developed in this research, these module options can be invented and produced by any third party vendors or the end-users themselves.

As mentioned, the customer can select the module on the strap to get the final product. Due to the large variation in the module options and use constraints, the end product is usually not the optimal one to satisfy the exact requirements. Therefore, the developed innovation toolkit with multi-level optimisation toolkit can be employed to obtain an optimised and individualised smartwatch.

5.2 MODELLING OF THE SMARTWATCH

![Configuration diagram for different variations of BLOCKS smartwatch](Image)

*Figure 5.2 Configuration diagram for different variations of BLOCKS smartwatch*
As described in the previous section, variation in different configurations along with different parameters for an OPAP can be represented by an AND-OR tree diagram. Figure 5.2 illustrates an AND-OR tree with all module options.

A feasible smartwatch configuration can be created with this AND-OR tree structure. Each node in this configuration tree diagram can be described by parameters, so thus the smartwatch configuration. A feasible smartwatch configuration and its parameters created from the AND-OR tree are indicated in figure 5.3.

Table 5.2 summarises a few of the parameters for selected feasible smartwatch configurations. These values indicate one set of values of various parameters. These parameters will be different for different configurations, based on blocks (modules) selected by the customer.

Table 5.2 Parametric values of different characteristics of selected feasible smartwatch configuration

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Memory</td>
<td>512MB RAM/ 4GB Flash (ePOP)</td>
</tr>
<tr>
<td>Display</td>
<td>1.39” AMOLED 400 x 400 Touchscreen Round display</td>
</tr>
</tbody>
</table>
Modelling represented in Figure 5.2 has considered only those modules which have two or more than two module options available for end-users. As this case study product is in the earlier stage of development, the number of modules having two or more than two module options are limited, only six modules, as depicted in Figure 5.2. In later stages of this product or other OPAP products, a number of modules having two or more than two module options will not be limited as many third-party module options suppliers will be available to provide more module options. The tree diagram can easily be scaled up to encompass those situations with more than six modules.

5.2.1 Evaluation measures for selected feasible smartwatch configuration

For this case study, seven customer evaluation measures have been selected. These evolution measures include five performance measures and two cost measures. Table 5.3 summaries all of these evaluation measures.

*Table 5.3 Various evaluation measures for selected feasible smartwatch configuration*

<table>
<thead>
<tr>
<th>Evaluation measures</th>
<th>Unit</th>
<th>Representation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost evaluation measure</td>
<td>Product Cost</td>
<td>GBP (£)</td>
</tr>
<tr>
<td>Maintenance Cost</td>
<td></td>
<td>GBP (£)</td>
</tr>
<tr>
<td>Performance evaluation measure</td>
<td>Product Weight</td>
<td>Grams (g)</td>
</tr>
<tr>
<td>Battery backup</td>
<td></td>
<td>Hours (hrs)</td>
</tr>
</tbody>
</table>

Connectivity WIFI 802.11 b/g/n, BLE

Battery 445 mA h

Battery Backup time 2 days

Weight 70 g

Dimension 45mm X 11mm-Core

30mm X 6mm-One module
5.2.1.1 Product Cost \( (C_p) \)

The final cost of the smartwatch depends upon the type of blocks chosen by the end-user. BLOCKS store explains the cost of different modules individually. With every additional block (module) end-user add or remove, price changes accordingly. This cost is measured in GBP (£) and calculated once end-user finalised the blocks on the strap. Cost of the core of the smartwatch is £259 and cost of each subsequent blocks is £35.

\[
C_p = n \times 35 + 259 \tag{5.1}
\]

where \( n \) refers to the number of module options integrated on the platform.

5.2.1.2 Maintenance Cost \( (C_m) \)

This cost refers to costs associated with maintenance of the core and modules, as required during swapping of modules or upgradation. This cost is calculated based upon the type of module and the required maintenance. This cost is measured in GBP (£). The base cost for maintenance has been considered as £20. The end product with temperature with air pressure and humidity would need more maintenance cost than other module options. The maintenance cost for a few dominant module options can be calculated as per Equation 5.1.

\[
C_m = n \times 20 + \text{Excess} \tag{5.2}
\]

where \( n \) refers to the number of module options integrated on the platform. The excess term in this equation is used to consider the presence of some specific module which requires more maintenance than other usual module options. For this case study, a module option for temperature with air pressure and humidity, and Continuous Heart Rate Monitor will have an excess of £20, and all other module option will have zero excess.
5.2.1.3 **Product Weight** ($P_w$)

Different blocks on the strap cause change in weight of the smartwatch. Individual weight of blocks is given on the module catalogues. The final weight can be calculated by adding these weights with the weight of the core. The product weight is measured in grams (g). The weight of the core of the smartwatch is 50g with each block weighing 7g.

$$P_w = n \times 7 + 50$$

(5.3)

where $n$ refers to the number of module options integrated on the platform.

5.2.1.4 **Battery Backup** ($P_b$)

A block with low power would consume less energy than high power block. The battery backup will vary accordingly to the type of blocks selected for the final smartwatch. This backup is measured in the number of hours (hrs). The backup will depend upon two factors; one is the numbers of module options, and another is the type of extra battery module used.

$$P_b = b \times \frac{48}{445} + 48$$

(5.4)

where $b$ represents the capacity of the extra battery module options and 48 (hrs) is default battery backup by each block. Value of $b$ can be taken from Table 5.4.

<table>
<thead>
<tr>
<th>Extra battery module option</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b$ (mA h)</td>
<td>95</td>
<td>190</td>
<td>285</td>
<td>380</td>
</tr>
</tbody>
</table>

Table 5.4 Extra battery module option

5.2.1.5 **Response Time** ($P_t$)

This measure denotes performance of the smartwatch in terms of slow or fast interface, leggy or quick performance, based on the extra processing required for module added by end-users. This measure helps to maintain the performance of the end product to the expectation. This is measured in seconds (sec). The base response time can be taken as 5 milliseconds (ms); this will increase as per the number of module options attached on the platform.

$$P_t = n \times 0.005$$

(5.5)
5.2.1.6 **Extra Features (P\(_f\))**

With every other block, it adds to new features which increase the utility of the smartwatch for end-users. Sometime for the same cost, the customer might prefer one module over other. This evaluation measure ranks end-user’s priority in terms of a number of extra features provided. This evaluation measure is measured in rank on the scale of 1 to 10. Where 10 refers best possible satisfaction with additional feature and 1 is the least possible.

5.2.1.7 **Ease of Access (P\(_e\))**

This measure is included to indicate the ease of access to different features added on the strap. For some user, how easy the smartwatch performs certain function become the deciding factor. The customer might find voice activation more convenient than touch activation. Thus, voice activation will have more ease of access. This measure also measured on the scale of 1 to 10 rank.

This research has only considered cost and performance evaluation measures for empirical validation. This was done due to the fact that these two evaluation measures are predominantly used as evaluation measures in literature and practise for such optimisation models. In a real implementation, there could be more than these two evaluation measures based on a particular product or application. As this model is developed using a tree diagram, the inclusion of more evaluation measures will not affect the way the toolkit is used. Other evaluation measures along with respective indices can simply be added and input in the equation 4.8 for overall customer satisfaction index, as per the application.

5.2.2 Evaluation indices

Table 5.5 summarises different evaluation indices associated with various evaluation measures selected for this case study.

<table>
<thead>
<tr>
<th>Product Cost</th>
<th>Maintenance Cost</th>
<th>Product Weight</th>
<th>Battery backup</th>
<th>Response time</th>
<th>Extra features</th>
<th>Ease of access</th>
</tr>
</thead>
</table>

*Table 5.5 Evaluation measures and respective evaluations indices*
<table>
<thead>
<tr>
<th>$C_p$ (£)</th>
<th>$I_p$</th>
<th>$C_m$ (£)</th>
<th>$I_m$</th>
<th>$P_w$ (g)</th>
<th>$I_w$</th>
<th>$P_b$ (hrs)</th>
<th>$I_b$</th>
<th>$P_t$ (sec)</th>
<th>$I_t$</th>
<th>$P_{i}$ (rank)</th>
<th>$I_{i}$</th>
<th>$P_e$ (rank)</th>
<th>$I_e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>259</td>
<td>1.0</td>
<td>20</td>
<td>1.0</td>
<td>50</td>
<td>1.0</td>
<td>48</td>
<td>0.1</td>
<td>0.01</td>
<td>1.0</td>
<td>0.1</td>
<td>1</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>294</td>
<td>0.9</td>
<td>40</td>
<td>0.9</td>
<td>57</td>
<td>0.9</td>
<td>53</td>
<td>0.2</td>
<td>0.02</td>
<td>0.9</td>
<td>2</td>
<td>0.22</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>329</td>
<td>0.8</td>
<td>60</td>
<td>0.8</td>
<td>67</td>
<td>0.8</td>
<td>58</td>
<td>0.3</td>
<td>0.03</td>
<td>0.8</td>
<td>3</td>
<td>0.35</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>364</td>
<td>0.7</td>
<td>80</td>
<td>0.7</td>
<td>71</td>
<td>0.7</td>
<td>63</td>
<td>0.4</td>
<td>0.04</td>
<td>0.7</td>
<td>4</td>
<td>0.55</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>399</td>
<td>0.6</td>
<td>100</td>
<td>0.6</td>
<td>78</td>
<td>0.6</td>
<td>68</td>
<td>0.5</td>
<td>0.05</td>
<td>0.6</td>
<td>5</td>
<td>0.65</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>434</td>
<td>0.5</td>
<td>120</td>
<td>0.5</td>
<td>85</td>
<td>0.5</td>
<td>73</td>
<td>0.6</td>
<td>0.06</td>
<td>0.5</td>
<td>6</td>
<td>0.80</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>469</td>
<td>0.4</td>
<td>140</td>
<td>0.4</td>
<td>92</td>
<td>0.4</td>
<td>78</td>
<td>0.7</td>
<td>0.07</td>
<td>0.4</td>
<td>7</td>
<td>0.88</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>504</td>
<td>0.3</td>
<td>160</td>
<td>0.3</td>
<td>99</td>
<td>0.3</td>
<td>83</td>
<td>0.8</td>
<td>0.08</td>
<td>0.3</td>
<td>8</td>
<td>0.90</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>539</td>
<td>0.2</td>
<td>180</td>
<td>0.2</td>
<td>106</td>
<td>0.2</td>
<td>88</td>
<td>0.9</td>
<td>0.09</td>
<td>0.2</td>
<td>9</td>
<td>0.95</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>574</td>
<td>0.1</td>
<td>200</td>
<td>0.1</td>
<td>113</td>
<td>0.1</td>
<td>93</td>
<td>1.0</td>
<td>0.10</td>
<td>0.1</td>
<td>10</td>
<td>1.0</td>
<td>10</td>
<td></td>
</tr>
</tbody>
</table>

The least square curve fitting method is used to covert these evaluation measures into non-linear continuous evaluation indices equations. These equations provide evaluation indices as a function of parameters selected for the optimisation model.

\[ I_p = a_{0i} + a_{1i}C_p + a_{2i}C_p^2 + a_{3i}C_p^3 \]  \hfill (5.6)

Using Table 5.5 for the curve fitting,

\[ I_p = 1.74 - 2.8571C_p + 1.0036C_p^2 - 6.9027C_p^3 \]  \hfill (5.7)

\[ I_m = a_{0i} + a_{1i}C_m + a_{2i}C_m^2 + a_{3i}C_m^3 \]  \hfill (5.8)

Similar to the previous equation, using table 4 for the curve fitting,

\[ I_m = 1.1 - 0.005C_m + 1.7322C_m^2 - 4.7812C_m^3 \]  \hfill (5.9)

\[ I_w = a_{0i} + a_{1i}P_w + a_{2i}P_w^2 + a_{3i}P_w^3 \]  \hfill (5.10)

\[ I_w = 1.2831 + 2.9369P_w - 2.154P_w^2 + 8.5857P_w^3 \]  \hfill (5.11)
\[ I_p = a_{oi} + a_{11}P_b + a_{21}P_b^2 + a_{31}P_b^3 \]  
(5.12)

\[ I_b = -0.15 + 0.025P_b - 3.5489P_b^2 + 1.0516P_b^3 \]  
(5.13)

\[ I_t = a_{oi} + a_{31}P_t + a_{21}P_t^2 + a_{31}P_t^3 \]  
(5.14)

\[ I_t = 1.1 - 10P_t + 7.6218P_t^2 - 4.9725P_t^3 \]  
(5.15)

\[ I_f = a_{oi} + a_{11}P_f + a_{21}P_f^2 + a_{31}P_f^3 \]  
(5.16)

\[ I_f = -0.0683 + 0.1489P_f + 0.0028P_f^2 + 0.0007P_f^3 \]  
(5.17)

\[ I_e = a_{oi} + a_{11}P_e + a_{21}P_e^2 + a_{31}P_e^3 \]  
(5.18)

\[ I_e = -0.0683 + 0.1489P_e + 0.0028P_e^2 + 0.0007P_e^3 \]  
(5.19)

The optimisation function for the first level of optimisation or parameter optimisation is formulated with the overall customer satisfaction index. This customer satisfaction index is derived by assigning a weighting factor to each evaluation index and taking a weighted average. Different weighting factors for each evaluation index are shown in Table 5.6.

**Table 5.6 Weighting factor for various evaluation indices**

<table>
<thead>
<tr>
<th>Evaluation Index</th>
<th>( I_p )</th>
<th>( I_m )</th>
<th>( I_w )</th>
<th>( I_b )</th>
<th>( I_t )</th>
<th>( I_f )</th>
<th>( I_e )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weighing factor</td>
<td>0.7</td>
<td>0.6</td>
<td>0.5</td>
<td>0.7</td>
<td>0.5</td>
<td>0.8</td>
<td>0.4</td>
</tr>
</tbody>
</table>

Therefore, the objective function for the parametric optimisation is:

\[
CS(X) = \frac{[W_1I_p + W_2I_m + W_3I_w + W_4I_b + W_5I_t + W_6I_f + W_7I_e]}{W_1 + W_2 + W_3 + W_4 + W_5 + W_6 + W_7}
\]

(5.20)

Using various weighting factors into the equation,

\[
CS(X) = \frac{[0.7I_p + 0.6I_m + 0.5I_w + 0.7I_b + 0.5I_t + 0.8I_f + 0.4I_e]}{0.7 + 0.6 + 0.5 + 0.7 + 0.5 + 0.8 + 0.4}
\]

(5.21)
Putting the value of various evaluation indices from equation 5.6 to 5.19 into equation 5.21, the objective function for the multi-level optimisation can be obtained. The calculation for obtaining the objective function is explained in Appendix E.

\[
CS(X) = \left[ -54439.04n^3 - 1.11 \times 10^6n^2 - 8.047 \times 10^6n + 0.0002b^3 + 0.2867b^2 + 124.548b + 1.983 \times 10^7 \right] 
\] (5.22)

5.2.3 The assumptions for the case study

The Case study is used to demonstrate the applicability of the innovation toolkit to optimise the end product in MI with OPAP. Since the insights for this case study are obtained from platform producers, i.e. BLOCKS; this analysis is based on a few assumptions, as follows,

1. The value of two evaluation measures, Extra features and Ease of access have been taken on a neutral standpoint for first configuration as this will vary as per individual end-user.

2. The value of weighting factors has been assumed to illustrate the parametric validation of the multi-level optimisation model. As per end-user preference, this model will provide individualised and an optimised value of overall customer satisfaction index.

3. For the GLONASS receiver module option, the value of \( P_l \) is more than that of GPS receiver module option.

4. For the voice activation button module option, the value of \( P_e \) is more than that of a touch activated button module option.

5. For the continuous heart rate monitor module option, the value of \( P_l \) is more than that of an intermittent heart rate monitor module option.

6. For the temperature with air pressure module option, the value of \( P_l \) is more than that of a temperate module option.

7. For the high-power LED module option, the value of \( P_l \) is more than that of a low power LED module option.

8. Uniform product purchase cost and maintenance cost for each module option are taken, as explained in the sections 5.2.1.1 and section 5.2.1.2.
In the presence of end-user preferences and user data, this toolkit would provide more accurate and individualised results.

5.3 Optimisation of BLOCKS Smartwatch Based on Developed Innovation Toolkit

The first generation of this OPAP is created from AND-OR tree shown in Figure 5.2. For this case study, 5 configurations are created in every generation. Different individuals are listed in table 5.7. Each individual feasible configurations can be described by different parametric values. For each feasible configuration in any generation, the first level of parametric optimisation is employed to maximum overall customer satisfaction index as per the above equation. For this parametric validation on a selected case study, two parameters, the number of module types (n) and extra battery module number (b) are selected as the core parameter for optimisation.

For a feasible configuration, shown in Figure 5.3, the first level of optimisation can be employed as follows:

\[ D_1 = (\text{Temperature with air pressure, Intermittent heart rate monitor, Low power LED, Touch activated smart button, GPS receiver, 95 mA h}) \]

(5.23)

The first level of optimisation can be formulated as follows (it is assumed that it will same for all the configuration):

\[
\begin{align*}
\text{Max}_{\text{wrt } n, b} \ CS(n, b) \\
\text{Subject to:} \\
1 \leq n \leq 6 \ , \ n \in I \\
90 \leq b \leq 400
\end{align*}
\]

(5.24)

(5.25)

(5.26)

The optimal values of the selected variables are as follows,

\[ n = 6 \]

(5.29)

\[ b = 95 \]

(5.30)
The best overall customer satisfaction index for these optimal values is,

\[ CS = 0.783 \]  \hspace{1cm} (5.29)

This value of CS is used as the fitness measure of this configuration.

Five configurations along with their optimal CS values are shown in the following Table 5.7.

**Table 5.7 First generation configurations along with their optimal CS values**

<table>
<thead>
<tr>
<th>Configuration Number</th>
<th>Configuration</th>
<th>Fitness (CS Value) for GA</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Temperature with Air Pressure, Intermittent Heat rate monitor, Low Power LED, Touch Activated, GPS Receiver, 95 mA h</td>
<td>0.783</td>
</tr>
<tr>
<td>2</td>
<td>Temperature with Air Pressure, Intermittent Heat rate monitor, Low Power LED, Touch Activated, GPS Receiver, 190 mA h</td>
<td>0.750</td>
</tr>
<tr>
<td>3</td>
<td>Temperature with Air Pressure &amp; Humidity, Intermittent Heat rate monitor, High Power LED, Voice Activated, GPS Receiver, 190 mA h</td>
<td>0.815</td>
</tr>
<tr>
<td>4</td>
<td>Temperature with Air Pressure &amp; Humidity, Continuous Heat rate monitor, High Power LED, Voice Activated, GLONASS Receiver, 285 mA h</td>
<td>0.781</td>
</tr>
<tr>
<td>5</td>
<td>Temperature with Air Pressure &amp; Humidity, Continuous Heat rate monitor, High Power LED, Voice Activated, GLONASS Receiver, 380 mA h</td>
<td>0.693</td>
</tr>
</tbody>
</table>

From the first generation of these configurations, two parent configurations are selected to obtain configurations of the next generation. After selecting the parent configurations from the first generation, three operations of genetic programming: reproduction, crossover, and mutation are used.
From equation 4.25, the reproduction is started by the roulette wheel selection method. Sum of fitness of all feasible configuration selected for the first generation is 3.822. Two random numbers of 3.182 and 1.105 are generated using a random number generator tool from Random.org (2019).

Based on these random numbers and from question 4.25, configuration no. 5 and configuration no. 2 are used for reproduction. These two configurations are shown in Figure 5.4 and Figure 5.5.
The crossover operation is then used with these two configurations to obtain the next generation of feasible configurations. As described in Chapter 4, the threshold crossover probability is taken as 0.55 for this work. Calculation of the cross-over probability for these two configurations is done by using equation 4.26. For the first generation, the value of $f_{bigger}$ is 0.750, and the value of $f_{avg}$ is 0.764. Since,

$$f_{bigger} < f_{ave}$$  \hspace{1cm} (5.30)

So,

$$p_c = 1$$  \hspace{1cm} (5.31)

Since the cross-over probability is larger than the threshold cross-over probability, the crossover will be used for these two configurations from the first generation to obtain configurations of the second generation. The module options selected for the cross-over operation are shown in the left part of Figure 5.6, in the dashed boxes. Once the module options to cross-over are identified, these two module options are swapped to obtain two new configurations in the second generations. These operations are shown in Figure 5.6. CS values for configuration 1 and configuration 2 of the second generation are 0.692 and 0.770.
After the cross-over operation, mutation is used for both of the new configurations obtained for the second generation. Equation 4.27 is used to calculate the mutation probability for both of the new configurations. As mentioned in Chapter 4, the threshold mutation probability is taken as 0.4 for this work. For the mutation probability of the first configuration of the second generation,

\[ f < f_{ave} \]  \hspace{1cm} (5.32)

so,

\[ p_m = 0.5 \]  \hspace{1cm} (5.33)

Since the mutation probability is larger than the threshold mutation probability, mutation is used for this configuration. For the mutation probability of the second configuration of the second generation,

\[ f \geq f_{ave} \]  \hspace{1cm} (5.34)

Figure 5.6 Cross-over within configuration 2 and configuration 5 of the first generation to obtain the second generation
So,
\[
p_m = 0.5 \left( \frac{f_{max} - f}{f_{max} - f_{ave}} \right) = 0.34
\]
(5.35)

Since the mutation probability is smaller than the threshold mutation probability, mutation is not required for this configuration. Figure 5.7 illustrates mutation for configuration 1 of the second generation.

**Figure 5.7 Mutation operation on configuration 1 of the second generation**

Operations mentioned in the previous paragraphs have been applied to other configurations in the first generation to obtain the second generation. Various configurations with their CS values are shown in Table 5.8.
### Table 5.8 Second generation configurations along with their optimal CS value

<table>
<thead>
<tr>
<th>Configuration Number</th>
<th>Configuration</th>
<th>Fitness (CS value) for GA</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Temperature with Air Pressure, Continuous Heat rate monitor, Low Power LED, Touch Activated, GPS Receiver, 285 mA h</td>
<td>0.830</td>
</tr>
<tr>
<td>2</td>
<td>Temperature with Air Pressure &amp; Humidity, Intermittent Heat rate monitor, High Power LED, Voice Activated, GLONASS Receiver, 380 mA h</td>
<td>0.770</td>
</tr>
<tr>
<td>3</td>
<td>Temperature with Air Pressure, Intermittent Heat rate monitor, High Power LED, Voice Activated, GPS Receiver, 190 mA h</td>
<td>0.732</td>
</tr>
<tr>
<td>4</td>
<td>Temperature with Air Pressure &amp; Humidity, Intermittent Heat rate monitor, High Power LED, Touch Activated, GLONASS Receiver, 190 mA h</td>
<td>0.751</td>
</tr>
<tr>
<td>5</td>
<td>Temperature with Air Pressure, Continuous Heat rate monitor, Low Power LED, Touch Activated, GPS Receiver, 190 mA h</td>
<td>0.793</td>
</tr>
</tbody>
</table>

The value of the average CS for the second generation is 0.775 which is higher than the average for the first generation (0.764). This process can be further continued with the help of automated innovation toolkit to obtain better average fitness of future generations. This work only considers two generations for the GA configuration optimisation. From Table 5.8, it can be seen that configuration 1 of the second generation is the optimal configuration with maximum customer satisfaction index. Thus, the optimised configuration for the smartwatch is,

\[ D_1 = (\text{Temperature with air pressure, Continuous heart rate monitor, Low power LED, Touch activated smart button, GPS receiver, 285 mA h}) \]  

(5.36)

In summary, this chapter demonstrates the applicability of the developed innovation toolkit on an existing OPAP product, BLOCKS smartwatch. This case study was investigated on the parametric level to illustrate the effectiveness of the innovation toolkit on the existing market.
products. Insights for this validation were developed by industrial engagements with a semi-structured interview. Interview results are used as a means of obtaining product details and constraints for the optimisation model for this case study exploration and further parametric validation of introduced innovation toolkit. With the help of the developed innovation toolkit, two generations of this smartwatch are created. The value of the average CS for the second generation (0.775) is higher than the average CS of the first generation (0.764), thus producing a better generation with feasible configurations. After comparing all the configurations in the second generation, it was found that configuration 1, as shown in Equation 5.36 is the most optimised one. The number of iterations for the GA for this case study are limited in this thesis. However, these iterations can be further increased with the help of automation of the Innovation toolkit. Based on the weighting factors selected by the end-user, the innovation toolkit would provide different end products which would be most individualised and optimised.

**CASE STUDY 2: GOOGLE ARA**

5.4 **Extension to the Parametric Validation with another Case Study Product**

This section is an extension to chapter 5, aimed to test and extend the demonstration of parametric validation of the developed innovation toolkit with a different product than explained in the first part of this chapter. This would further present a more holistic evaluation of the toolkit. The product used to illustrate the applicability of the innovation toolkit in the previous chapter, an OPAP smartphone Google ARA, is selected for this evaluation.

Parametric details used to illustrate the applicability of the innovation toolkit mentioned in chapter 4 were taken from the Modular development kit (MDK), a guide for the development of modular technology that Google has provided to developers (Project ARA by Google, 2016). However, to evaluate the toolkit with actual module options used by Google ARA in the pilot market study, parametric details of the same modules are adapted from Colombo, Shougrarian, Sinha, Cascini, and de Weck (2020) for this case study here and listed in Table 5.9. Different modules include a camera module, battery module and screen module. For camera
module, two different module options are provided: amateur quality and professional quality. For battery module, three different module options with a capacity of 250 mA h, 500 mA h and 750 mA h are available to choose from. For the screen module, two different module options are provided: mid resolution and high resolution. For Google ARA, these module options are invented and produced by Google, but in the framework developed in this research, these module options can be invented and produced by any third party vendors or the end-users themselves.

**Table 5.9 Different modules of Google ARA with their module options and primary function**

<table>
<thead>
<tr>
<th>Module</th>
<th>Module options</th>
<th>Primary Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Camera</td>
<td>1. Amateur quality</td>
<td>Taking pictures/video</td>
</tr>
<tr>
<td></td>
<td>2. Professional quality</td>
<td></td>
</tr>
<tr>
<td>Battery</td>
<td>1.250 mA h</td>
<td>Storing and providing energy</td>
</tr>
<tr>
<td></td>
<td>2.500 mA h</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3.750 mA h</td>
<td></td>
</tr>
<tr>
<td>Screen</td>
<td>1. Mid resolution</td>
<td>Displaying information</td>
</tr>
<tr>
<td></td>
<td>2. High resolution</td>
<td>Receiving inputs</td>
</tr>
</tbody>
</table>

The variations of this OPAP smartphone with different potential module options for selected modules are shown in Figure 5.8 with an AND-OR configuration tree diagram.
From this AND-OR tree diagram, different combinations of feasible smartphone can be obtained. One such feasible configuration is illustrated in Figure 5.9.

**Figure 5.8** An OPAP smartphone, Google ARA, with parametric details of different module options.

![Diagram showing AND-OR tree configuration](image)

**Figure 5.9** A feasible OPAP smartphone configuration with module options’ parametric details from AND-OR configuration tree diagram of Figure 5.8.

Table 5.10 summarises different parameters for selected feasible smartphone configurations. These values indicate one set of values of various parameters. These parameters will be different for different configurations, based on modules selected by the end-user.

**Table 5.10** Parametric values of different characteristics of selected feasible OPAP smartphone configuration

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Camera</td>
<td>Professional quality</td>
</tr>
<tr>
<td>Battery</td>
<td>500 mA h</td>
</tr>
<tr>
<td>Screen</td>
<td>Mid resolution</td>
</tr>
</tbody>
</table>

For this case study, four customer evaluation measures have been selected. These evaluation measures include one cost measures and three performance measures, as shown in Table 5.12.

**Table 5.11** Various evaluation measures for selected feasible smartwatch configuration

<table>
<thead>
<tr>
<th>Evaluation measures</th>
<th>Unit</th>
<th>Representation</th>
</tr>
</thead>
</table>
The product cost for different alternative configurations can be determined based on individual cost from different module options suppliers, so thus the product weight and battery backup. It can be seen in the previous case study validation in this chapter that product cost was evaluated using a parametric relation between cost of each module options and the number of module options added to the smartwatch’s open platform. That was achieved with the fact that the cost of each of the module options has a definite value and was same as others. This led to a definite mathematical relationship, such as eq. 5.1 to derive different costs associated with different combinations of module options for all possible configurations of the OPAP product.

In this case study product, module options of camera module and screen module do not have a definite parametric value. This situation presents a challenge in terms of deriving a mathematical co-relation for different evaluation measures such as product cost, product weight. Those evaluation measures such as extra features where evaluation measure solely depends upon the end-users’ decision, this situation will not present a difference than discussed in the previous case study in this chapter. In the absence of mathematical relations for evaluations measures, it would be difficult to generalise the calculation of the evaluation measures for a range of different product configurations. It would further be challenging to generate the evaluation indices for different evaluation measures and thus the overall satisfaction index for calculation of the first level of optimisation. To summarise, the approach demonstrated in the first part of this chapter for parametric validation of the developed innovation toolkit would not be applicable and thus can not be used for parametric validation with this case study product. This presents with a limitation to the applicability of the innovation toolkit.
However, in a different approach, a mathematical equivalent can be generated for those module options which does not have a parametric value to be used for the derivation of evaluation measures and respective evaluation indices. This provides an opportunity for further investigation in future work. The market implementation of the developed innovation toolkit would need to consider the assumption explained in section 5.4.1 along with the situation explained in this part of chapter 5. In the presence of these considerations, end-user preferences and user data, this toolkit would provide more accurate and individualised results.

In summary, this part of chapter 5 presented more holistic evaluation of the developed innovation toolkit by considering a situation where this innovation toolkit would not be applicable in the existing form and would need further considerations in terms of parametric relations between different evaluation measures, indices and the objective function for the multi-level optimisation model.

5.5 LIMITATIONS OF THE PARAMETRIC VALIDATION

The empirical validation reported in this chapter should be considered in light of some limitations. The primary limitation of this validation is the absence of contribution from the end-user regarding preferences, weighting factors and input to some evaluation measures such as extra features evaluation measure, ease of access evaluation measure. In the absence of these data, this study assumed the value of mentioned measures on a neutral standpoint. In a different scenario, when end-users provide their preferences on these measures, the value of the customer satisfaction index from the optimisation model would provide a different result.

Besides the primary limitation mentioned above, this validation has considered constraints, evaluation measure and evaluation indices for particular case study products from consumer electronics. Type of evaluations measures and constraints used for the optimisation model would be different for different product categories. However, once different evaluation measures and their value ranges are obtained, these can be converted into respective evaluation indices value ranges. Table 5.13 summarises ranges for evaluation measures and their indices for the OPAP smartwatch discussed in the first part of this chapter. It can be seen
from this table that evaluation indices will remain within the range of 0 and 1, irrespective of the type of product and value of its evaluation measures.

Table 5.12 Range of evaluation measures and evaluation indices for the case study product

<table>
<thead>
<tr>
<th>Type of evaluation measures</th>
<th>Range of evaluation measures</th>
<th>Range of evaluation indices</th>
</tr>
</thead>
<tbody>
<tr>
<td>Product Cost</td>
<td>£ 259-574</td>
<td>0.1-1.0</td>
</tr>
<tr>
<td>Maintenance Cost</td>
<td>£ 20-200</td>
<td>0.1-1.0</td>
</tr>
<tr>
<td>Product Weight</td>
<td>50-113 g</td>
<td>0.1-1.0</td>
</tr>
<tr>
<td>Battery backup</td>
<td>48-93 hrs</td>
<td>0.1-1.0</td>
</tr>
<tr>
<td>Response time</td>
<td>0.01-0.10 sec</td>
<td>0.1-1.0</td>
</tr>
<tr>
<td>Extra features</td>
<td>1-10</td>
<td>0.1-1.0</td>
</tr>
<tr>
<td>Ease of access</td>
<td>1-10</td>
<td>0.1-1.0</td>
</tr>
</tbody>
</table>

The innovation toolkit and validation presented in this thesis is a manual one, comprising of a lengthy optimisation model. This is one aspect this thesis has considered beforehand. One other alternative approach for this innovation toolkit is based on game theory, briefly explained in section 4.3.1. This alternative approach would provide separate models for all three actors (end-user, platform producers and module options suppliers) which can be further combined to form an overall innovation toolkit. However, this alternative model was not suitable for automation and scaling up. On the other side, the innovation toolkit presented in this thesis is based on a tree-diagram approach which can easily be automated and can be scaled up based on the type of product and the number of module types.

In further studies, an automated form of the proposed innovation toolkit can be developed, and this validation can be carried out by considering different products from a range of product categories.
6 CONCLUSION AND RECOMMENDATIONS

The primary research goals of the thesis are to understand product design innovation and product individualisation using MI with OPAP. Increasing aspiration levels of customers are forcing companies to rethink their product development organisation, revise the use of technological innovation into products, and derive individualised products from them. The thesis has argued that the new product individualisation approach, MI, would fulfil the exacting needs of end-users by providing highly individualised and technologically advanced products. The thesis further the academic and industrial interest on product individualisation with the introduction of OPAP as a key enabler of MI. The OPAP comprises an open hardware platform, mass-produced by large manufacturers and multiple independent modules invented and produced by other smaller companies. It gives freedom to end users to integrate different modules into the platform as per their choice and thus producing highly individualised products. This type of product integration will be engaged with by the all actors involved in the design and aims to help them to be more creative and innovative. This thesis is positioned to connect established literature on customisation to innovative propositions for individualisation. The thesis sets the scope for MI with OPAP and provides a mean of promising opportunities to advance the field.

As MC is a growing interest area in academia as well in the industry, this thesis builds on and expands this interest area with the introduction of OPAP as a key enabler of MI. In terms of design, MI mainly discerns from mass customisation in three areas: MI expands the design space, MI embraces intangible customer experience, and MI enhances creativity and innovation through the democratisation of the product design process. The most significant extension of individualisation can be directly linked to the integration of experience not only in use but also in purchasing, order processing, inventing and producing components/modules, delivery, upgradation, maintenance, resale and being a producer. MI combines user-centric design with networked innovation. By linking all steps in the value chain, a world of possibilities opens for end-users and other actors. Also, this approach targets to translate good ideas into innovative products and services quickly.

This research is first of its kind in addressing the demand of the market to one with the help of product design for MI with OPAP. So, the first two chapters explained various key concepts
associated with this research. With the help of the schematics of introduced concepts, ecosystems, and comparison tables, a clear connection between the existing and proposed idea of product individualisation has been established. A framework for the MI ecosystem has been developed, describing the flow of various decisions including the selection of product platform, putting forward choices for module options and followed by integration of these modules into the platform. As this thesis introduces the MI ecosystem with OPAP, the roles of different actors have been explained (Chapter 2).

The first part of the thesis examines various product design and customisation approaches to identify different key areas needed to be focused to realise and implement the product design for MI in the market. The realisation of product design for MI with OPAP requires a whole set of new design principles, such as cross-connected design support system, access to everyone. One of the key areas investigated in this study is the Changes in traditional product design and customisation approaches. These changes include changes in Context, Ecosystem, Perspective, Vendor, Discipline, Competition, and Access. Change in the ecosystem is investigated thoroughly as a part of this research for strategic and technological integration. Another key area which was investigated is various components that need to be focused on. These components include Design & development, Manufacturing, Assembly, After services, and Sustainability, Adaptability, Upgradability. Development of different components of MI ecosystem requires innovative means of design, manufacturing and relevant infrastructure that have not been typically present in existing companies. The main idea behind value creation through MI is that the more stakeholders there are, the more innovative and technologically advanced can the product become.

Different key technologies such as IoT, AI, and product realisation are explored as enablers of MI in the market. The improved speed, processing power, evolution of customer relationship management (CRM) as a strategy, improvements in enterprise resource planning (ERP) software consistent with individualised needs, data warehousing, connectivity, and interfaces provide the required support to transit to new product design paradigm. New technologies allow for new ways to collaborate and coordinate across various discipline and between actors. These technologies help to create and develop new environments for actors to think about new options, to interact iteratively or to experiments with a different combination of module options into the end product. The latest information and communications
technologies has enabled the exchange of distributed sources a way faster. These technologies not only provide direct means to facilitate the support system for MI but also helps shape the strategic orientation of industrial firms towards OPAP. They help to forge closer links between market information and further technology development.

This thesis encourages excellence through the interdisciplinary network in the product design and development process. The outcome of the first part of the investigation in the thesis finds that highly sophisticated, socio-technical systems need to be developed which will require the collaboration of various academic disciplines and institutions. To realise and implement this approach in the market, future engineers need to look beyond their own specialisation and traditional business models (Chapter 4).

Following the insights from literature exploration of various key enablers of MI with OPAP, an industrial questionnaire survey was conducted. Results from this questionnaire were statistically analysed and presented in Chapter 4, for industrial implications. The survey yielded sufficient information to provide clear insights on different aspects of this new approach. Responses to Q.6 were significant in providing motivation for this thesis with 80% of responses indicating that MI would increase the intention and willingness of the end users to buy end products produced by this approach. Responses to Q.7 indicated that given the benefits of MI with open platform architecture, more than 80% of respondents would consider using a product designed with this approach. Responses to Q.8 are very motivating as 76% of responses are in some degree of agreement with the idea that MI will encourage creativity and innovation towards producing a highly individualised end product. Responses to Q.12 strengthen the notion that MI will be able to offer an innovative means towards sustainable and adaptable product design, as greater than 50% responses are in agreement and 27% responses are on neutral standpoint. Responses to Q.19 provide an interesting insight as more than 60% of the responses agreed that MI would reduce the technological unpredictability by uniting various professional on a solitary platform.

Some responses were concerned about the feasibility of the innovation management in terms of IPR, and acceptability by existing organisations. However, above 65% of the responses agreed that the end product would be more creative and innovative from MI, and offers more individualised and technologically advanced products. It was backed by the notion that the end product will be a result of the creativity and innovation of all the actors. This part of
research also put emphasised on the propositions from the initial investigation on various product customisation approaches that MI with OPAP provides adaptable, upgradable and sustainable end products as the product can be upgraded and reused by just changing the appropriate modules on the platform. These products can embrace change in technology, customer behaviour patterns, and requirements. Insights from this research can be used to formulate platforms for manufacturing of the future. MI with OPAP framework can be replicated and enhanced to support the next generations of rapidly changing manufacturing technologies.

Based on the explorative literature analysis, with practical insights from an industrial questionnaire survey, a framework for the Innovation toolkit for the end-user is developed, in the third part of the research (Chapter 4). A networked innovation toolkit describes a design environment which enables and empowers actors to formulate their requirements iteratively and transfer these into a producible solution by an iterative process with continuous live networked support from other actors in the OPAP ecosystem. The design of the optimisation model for the innovation toolkit has been approached in four different steps: Modelling of OPAP; Modelling of evaluation measures and evaluation indices with end-user preferences; Identification of the optimal module options for every configuration; Configuration optimisation. The thesis argued that the function of one module or module system could be optimised with other related modules or module systems with this innovation toolkit.

The innovation toolkit used a multi-level optimisation model to identify the optimal design configuration for OPAP to satisfy the exact needs of the end-users. Variations in product configurations with different module options in an OPAP are modelled by nodes in an AND-OR tree. The AND-OR with different nodes for module options provides a systematic framework to model large variations of OPAP configurations. The optimal module option for every interface with maximum overall customer satisfaction index is identified by constrained optimisation, followed by configuration optimisation to identify optimal OPAP configuration out of all the feasible configurations. Two case studies (OPAP products) have been used to demonstrate the applicability of this Innovation toolkit. The innovation toolkit is applied to two product platforms to illustrate the applicability of the proposed innovation toolkit. These case studies show that the developed innovation toolkit for Design for MI with OPAP can
readily be applied to this type of product development and will help end user to obtain optimised and highly individualised end product.

This innovation toolkit has also been employed on one existing OPAP market product from BLOCKS for industrial validation, in Chapter 5. This case study was investigated on the parametric level to illustrate the effectiveness of the innovation toolkit on the existing market products. Insights for this validation were developed by industrial engagements with a semi-structured interview. Interview results are used as a means of obtaining product details and constraints for the optimisation model for this case study exploration and further parametric validation of introduced innovation toolkit. With the help of developed innovation toolkit, two generations of this smartwatch are created. The value of the average CS for the second generation (0.775) is higher than the average CS of the first generation (0.764), thus producing a better generation with feasible configurations. After comparing all the configurations in the second generation, it was found that configuration 1 is the most optimised one. This case study demonstrates the applicability of the developed innovation toolkit on an existing OPAP product. Based on the weighting factors selected by the end-user, the innovation toolkit would provide different end products which would be most individualised and optimised.

As this thesis on MI is first of its kind in addressing the need of the market to one with the help of OPAP, it will open new frontiers and basis for new development in existing product design and customisation approaches. This work will also provide the basis for future research in the promising field of MI with OPAP. It will contribute in terms of academic advances across and within disciplines, including significant advances in understanding, methods, theory, and application related to product design for MI. The cross-connection between different actors involved in the design process of MI with OPAP would require new creative and innovative approaches. The thesis provides the necessary advancement in MI to motivate continued and renewed interests in design methods and tools to support the development of MI with OPAP further.

6.1 LIMITATIONS AND DIRECTION FOR FUTURE RESEARCH

Research into product design for MI using an OPAP is at an early stage, and it requires further industry led insights. This approach opens a new set of opportunities in terms of product
innovation. Development of the market ready MI requires empirical research to address different issues, including monetary and resource allocation to different actors. Different payoff functions for various actors can be formulated by considering respective constraints. The current framework for the ecosystem is developed considering the end-user’s perspective in the centre. This needs to be expanded by the inclusion of module options suppliers’ and platform producers’ perspectives. This approach also addresses the sustainability in product design in an innovative way which can be explored further. MI helps to obtain upgradable and adaptable end products. This aspect can be further be investigated and the scope this research presents can be utilised further.

This research used a case study to demonstrate the applicability of the developed innovation toolkit to optimise the end product in MI with OPAP. Since the insights for the case study are obtained from platform producers, i.e. BLOCKS; the analysis is based on a few assumptions from end-user’s side. The value of weighting factors has been assumed to illustrate the parametric validation of the multi-level optimisation model. As per end-user preference, this model will provide individualised and an optimised value of overall customer satisfaction index. This aspect of empirical validation can be further investigated by employing toolkit with real end-users with their weighting factors.

To realise and implement the developed innovation toolkit in the market, many other issues need to be addressed including optimisation of module option during the product operation stage and development the Innovation toolkit further considering the same. Different monetary aspects, IP rights, acceptance of this approach by existing designers are also need to be tested before implementation in the market. It opens a new set of opportunities which need to be studied further. For future research direction, the following areas are identified as promising opportunities to advance the research theme:

6.1.1 Design support system for platform producers and module options suppliers

The fulfilment of individualised product aspiration with OPAP requires alignment of decisions of the end user, platform producers, and module options suppliers. This thesis keeps end-user in the centre of the innovation toolkit, followed by the design support system for the end-user. This design support system can be further extended for platform producers and
module options suppliers. Extended collaborative design support systems are the core to support this product individualisation. These design support systems will be iteratively improved after market implementation and feedback. Henderson and Clark (1990) identified the risk of creating barriers to architectural innovation as one potential negative effect of open architecture which could be investigated further for all the actors.

In order to implement a broad and effective OPAP, a wider management strategy is required which would consider other actors’ decisions and priorities too. Suitability of a general design support system or specific and tailored to each product categories also needs to be investigated. Established strategies such as Enterprise Resource Planning (ERP) and Product Data Management (PDM) can be further tailored for OPAP product development. Further research in various coordination schemes in the logistic domain for different module options is needed. The ultimate goal is to develop a virtual enterprise that helps to create individualised products over the web-enabled design support system through coherently integrating networked production of module options and product platforms with supply management and sales-service support.

6.1.2 Economics of Open Platform Architecture Products

OPAP would need to incorporate more front-end issues such as economic evaluation of product integration, monetary models to share among different actors. Quantifying both the benefits and costs of OPAP is required in the product development in MI. The challenges of multi-actor participation and market uncertainties need further exploration. Influence of expanding into a new geographical and demographic market, adherence to new regulations, and new technologies need to be further investigated, on economies of OPAP.

Financial models both in terms of saving due to adaptable and upgradable, and revenues due to successful product performance in the market need to be developed. The economic justification of open platform architecture products requires the identification of appropriate measures and performance indicators which could characterise different outcomes of a MI with OPAP product development system.
6.1.3 OPAP during the product operation stage

As described in Chapter 2, specific add-on modules with specific nature and functionality would be provided when the end-users buy the product for the first time, and unknown add-on modules would be provided to replace or upgrade the product as per the user’s requirements which were not thought of at the time of purchase. The developed innovation toolkit only considered the specific add-on modules in this thesis. The innovation toolkit can further be enhanced for the unknown add-on modules or the module selected during product operation stage. The inclusion of unknown add-on modules would require consideration of adaptable design parameters along with un-adaptable design parameters. The values of parameters can be calculated from the change in requirements, working conditions and other product parameters based on design.

6.1.4 Sustainable products with OPAP

Besides acting as a key enabler of product design for MI, OPAP provides immense opportunities including providing sustainable end products. OPAP offers adaptability and upgradability in products as the end product can be upgraded and reused by just changing the appropriate modules. These products provide means to address economic, environmental, and social aspects of sustainability. This benefit of OPAP requires further attention and research.

In summary, abundant research opportunities exist in response to the emerging field of MI with OPAP aiming to leverage upon open systems, product platforms, and networked organisations.


Pensworth, L. (2019). What Happened to Project Ara?


## APPENDIX A: QUESTIONNAIRE SURVEY WITH RESPONSES

<table>
<thead>
<tr>
<th>Q. No</th>
<th>Survey Questions</th>
<th>Survey Response</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><strong>Product Design for Mass Individualisation</strong></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Are you familiar with the concept of product design for MI (Mass Individualisation)?</td>
<td><img src="image" alt="" /></td>
</tr>
<tr>
<td>2</td>
<td>What kind of industry are you affiliated with?</td>
<td><img src="image" alt="" /></td>
</tr>
<tr>
<td>3</td>
<td>Which statement best describes how innovative could be the new product design paradigm (MI) for product design?</td>
<td><img src="image" alt="" /></td>
</tr>
<tr>
<td>4</td>
<td>Which statement best describes how relevant the idea of product design for MI is for your industry?</td>
<td><img src="image" alt="" /></td>
</tr>
<tr>
<td>5</td>
<td>What do you think about the suitability of this product design concept to a particular type of industry?</td>
<td><img src="image" alt="" /></td>
</tr>
<tr>
<td>6</td>
<td>This product design paradigm would enhance the intention and willingness of end-users to buy products. How would you agree with this statement?</td>
<td><img src="image" alt="" /></td>
</tr>
<tr>
<td>7</td>
<td>If you had the opportunity, would you consider purchasing a product designed with this approach?</td>
<td><img src="image" alt="" /></td>
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<tr>
<td>Product Design Innovation</td>
<td></td>
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<td>---------------------------</td>
<td></td>
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<tr>
<td>8</td>
<td>Product design for MI encourages creativity and innovation. Do you agree with this statement?</td>
<td></td>
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<tr>
<td>9</td>
<td>Which statement best describes how effective you think the new product design paradigm (MI) would be for satisfying customers' needs?</td>
<td></td>
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<tr>
<td>10</td>
<td>The inclusion of so many actors in product design opens the door for the innovation opportunities. How do you agree with this statement?</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Different participant companies with different expertise will be able to provide their best in field modules for users which will make the product most advanced and innovative? How would you agree with this statement?</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>This product design paradigm also provides an innovative means for sustainable product design as the end product is adaptable and upgradable. Do you agree with this statement?</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>End-users can develop a product module for their products and can contribute towards product innovation. How would you agree with this statement?</td>
<td></td>
</tr>
</tbody>
</table>
Strategical and Technological Consideration

14. Open platform architecture products (OPAP) expand the industrial boundaries and brings together different firms with their own expertise on a single platform. How would you consider that this is an opportunity for smaller companies to be a part of a larger system?

Product design for MI changes the industrial structure from vertical (different actor in a single organisation) to horizontal (different actors in different organisations). How do you think it affects the innovation in organisations?

This new product design paradigm helps to encourage a positive competition between companies by giving them equal opportunities to invent and produce modules. Do you agree with this statement?

Access to resources by cross networking between different actors is one of the key advantages of this product design paradigm. How important you think this would be for product innovation?

Networking between different actors at the same level and guidance by the platform manufacturers provides the best of the innovative technology available. Do you agree with this statement?

This approach would decrease the technological uncertainty caused by rapidly changing product technology in the market. Do you agree with this statement?
<table>
<thead>
<tr>
<th>Practical Suggestions</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
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<td>28</td>
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<td>29</td>
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</tbody>
</table>

Inertia and lack of capabilities to adapt to the paradigm, especially on the part of incumbents, IP Protection, Information management, resistance to change, Complexity; IP, profit-based approach, misuse or imposition; Depends on the product; People at various stages in life wanting to be the same as others; Economic Stability; the complexity, Ease of use - end-users could find it difficult to employ these technologies; Debate over IP - sounds a lot like open source. How would we differentiate our product from competitors?; Understanding by those involved; linking the stakeholders; People do not like to use new platforms. They only use the platform which they are familiar; Legal and company IP. Flexibility, Agility to deploy new modules and improvements for products with the possibility to serve new customer segments. Speed could be an improvement, Organisational capabilities and innovation process (lean, stage/gate, agile, open innovation, etc.), Distinctness.

Depends on who owns what, Difficult to forecast, Seems context specific, Hard to generalise.

Organisational Culture, Senior management leadership in adopting this paradigm, Difference between firms and startup, Product dependent.
## APPENDIX B: IMAGE REPRODUCTION PERMISSION FOR FIGURE 2.2

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Nov 16, 2018

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                        | London, SW7 2DB  
                        | United Kingdom  
                        | Attn: Mr. Ravi K Sikhwal |
| Publisher Tax ID       | EU826007151    |
| Total                 | 0.00 GBP       |
Dear (Participant name),

We are doing research on Product design for Mass Individualisation (Ravi Sikhwal and Peter Childs) and its implication on existing Product Design approaches in the Market.

We are writing to request your participation in a short survey. This survey is an attempt to get feedback on the proposed product design innovation approach. We would be really grateful if you could spare some time and complete this survey. Your participation in this survey is completely voluntary and you may opt out of any question. All the responses will only be used for statistical purposes and will be reported only in aggregated form. This survey consists of multiple choices and text answer questionnaires with optional comment section. It should not take you more than 10 minutes to complete it.

To take this survey, please click on the following link:

https://imperial.eu.qualtrics.com/SE/?SID=SV_8nRYVfHnyv2za8R

If you have any questions about this survey, or difficulty in accessing the site or completing the survey, please let us know.

In return of this survey participation, we will offer a pre-publication of the research outcomes.

Thank you very much indeed in advance for providing this important feedback.

Regards

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........................................
APPENDIX D: INTERVIEW INSIGHTS ON BLOCKS

This Appendix presents responses to the interview conducted to obtain insights for a case study on BLOCKS. Questions with respective responses are as follows:

1. What was the opportunity you recognised when starting BLOCKS?

Well, there is a real story like other start-ups to tell. Once when I had a discussion about starting a company with a friend of mine, he added that he was interested in human computer interface research and wasn't very much into health. We started brainstorming about which product we'd like to build. We were interested in building some product and put it on Kickstarter. We could not agree on what would be the perfect kind of smartwatch for both of us. I wanted health features, and he wanted experimental features for gesture control. So out of this debate, we kind of came up with the idea of BLOCKS.

2. What do you believe are the two main success factors behind Blocks?

If you see ARA and other example based on modular architecture, they couldn't survive as they didn't address points due to which blocks is been so good. I mean I think Google ARA can survive very much. I think most of the products themselves have to target a certain niche of people. So I don't think BLOCKS as a product can serve the needs of all smartwatch users and not all kinds of customers who would like to have a much more product. Some people prefer to have a lot of choice and other people prefer to have simplicity. So when they go shopping, they're just given options and B and C, and they just choose the kind of people who like to plug and play. Usually people with an engineering background or software engineers and so on. So these are the people who tend to like this kind of product. So I think we focused on those people with the Kickstarter platform and we received a lot of support in the terms of monetary and otherwise. I think that was kind of the main success behind BLOCKS was that we just targeted the right kind of users as these are the people that basically like to tinker and play and that's great.

3. What changes affecting the mass individualisation industry have you recognised over the last years?

I think the whole world was open for innovation and hardware in 2013-14 because the cost of producing hardware decreased significantly at the time or at least prototyping with hardware. So there was a lot of investor interest in hardware and a lot of companies opened up to experimenting with new ways of producing things. I think another thing to mention which is very important is that the incoming of IoT and 3D printers so all of this basically kind of poured in. All of the open source thinking and open software also poured into this idea. We can do the same with hardware as we can do with software. There was a lot of
experimentation since the 2012-13. I think that's when I started reading yeah. Most projects have failed, I think. In the last year, I have also seen a lot of companies kind of close their doors to this idea. It's natural because I think there was a lot of hype around it which wasn't well thought through. So I think, if we again go back to my point, one must endeavour individualization. The different product would focus on certain kinds of people and certain kinds of users. It still will be mass.

4. Which is one technological, economic or social trend influencing your business most?

As I mentioned, I think that the incoming of IoT and 3D printers so all of this basically kind of poured in. All of the open source thinking and open software also poured into this idea. We can do the same with hardware as we can do with software. But when companies like Google try to push it to the general consumer market, I think general consumer is not ready. So I've seen, for example LG shut their doors down on the modularity aspect. It was not useful in all areas except for the battery. The main thing was that it was not cost efficient. So I think the cost efficiency of making these products is probably the hardest thing. We live in a society of disposable products and products which have to be slim and small especially from an electrical perspective.

5. Can you explain a bit more how the mass individualisation of pathways in consumer electronics works?

There are certain factors that influence this dynamic. You know if the phones were not getting smaller every month every year then we would have a different thinking for that. But that was the case in the first year. And also we live in the world of, as I said disposable products because most of the consumer electronics companies today live on the model of annual replenishment, of the same stuff again. So their revenue models is built on this kind of annual substitute products. Apple is a perfect example of it. They've been doing it very successfully for the last 10 years. So I think given all these factors I think modularity and mass individualization kind of useful but it's very challenging for it to survive you know. But I think in the next five years or so there will be some successes, but basically these successes will be in very particular markets. I'm sorry for the long answer. So I went to a number of things I think I would see including 3D printing, open source software. All of these gave rise to this big hype. A lot of people have failed and now we're going to see some successes but they're going to be in very well focused markets I think. Also, I think planned obsolescence is an interesting aspect in this regard. Planned obsolescence is beneficial to certain companies like industrial companies.

A friend of mine just finished a business school and he's an EMT consultant. But he worked with this gentleman who was head of circular economy for world economic forum. He's going to be targeting various industrial processes to try and improve circle economy think tank thinking. So for example. If someone's producing a bottle of shampoo for a hotel, that bottle
should be made in such a way that this bottle can be not recycled but reused again and again before it gets thrown out. So I think some modularity could be a good compromise.

6. What are your core factors in the configuration process, also with regard to providing excellent customer experience?

I haven't thought about this. Obviously, when we were built on building blocks, we think of a platform with many participants. As a whole, I don't think that it is necessary to have many participants. Products can be built to be modular and be serviced by a single company. Also, some companies can provide many different components for most individualization of products. So it's not necessary for many actors to be in that room. I think that's kind of like my main thinking on all wasted blocks of different boxes anyway.

I think it's more about the user needs rather than the market. Of course, we could have many vendors but again the availability of vendors depends on so many factors. You know as in the competitiveness of these vendors whether there is a natural monopoly or not or whether there is a tendency towards natural monopoly because certain markets are more prone towards natural monopoly. For example, you mentioned space is a market where natural monopoly is very likely to happen. I had my previous research in MRI scanners or medical resonance imaging brain scanners. There is a natural monopoly that exists in this market because these products are so expensive that monopolies just tend to happen. I think the military industry is an example where there is very little communication exchange in where the free market is more difficult to induce. So I think the more expensive the product is the more the smaller the market itself. It is the more difficult for a platform with many third vendors to exist. And I've seen the same problem has happened to more eye scanners you know where they could be modular and they could be repurposed and they can be much more versatile. My answer is I think yes depends on the industry but I still think the user is probably the more important factor here.

7. What was your biggest mistake? This question is regarding your blocks and your experiment with this kind of opening up the product. Did you see any mistake you made while selecting this kind of architecture?

Small companies should not be doing much of this stuff. The problem is that modularisation is very expensive. We decided that we're going to modularise not just the design of the components of different sensors but we are also going to have the modules and have different shells and removable shells. We realized that making products modular increased the cost very much. We just didn't know that it would increase two or three fold. In some cases I mean obviously, once you produce at a mass you will drive the price down to the price down. I think that was a mistake like thinking that we could do modular from the start.
8&9. How do you access the future of Mass Individualisation? Can there be too much of a good thing? What are the success factors of mass individualisation companies?

It is good. It is exciting. The future of this kind of modular products is good. I definitely think that there is space for these products, as you mentioned, not only from the point of view of customers and individualized products but also from the point of view of cost reduction. The price you pay for environmental impact which because of the chronic waste is a big part of it. As the vendor if you're servicing the thin client. You know so being modular sometimes is cost effective for certain companies. Yes. Unfortunately, that's not true in all industries. So I think there's a big push right now. For these products, it's just in very specific sectors. Having spoken about the circular economy idea, I do think that. As we push towards more cost effective solutions you know in industrial products and natural processes, I think modernization will become the key aspect of it.

Maybe if I had to rethink it, I think weatherization is extremely important in B2B process more than B2C because educating the consumer is quite much harder because if you think about how consumers think is that they are impulsive and they are emotion driven. And the decisions that consumers make are primarily based on human desires rather than cost efficiency and logical thinking whereas a few servicing businesses who need to think about long term benefit, cost benefit, and then their decision making. And that attitude towards modular products will be very different. So that's kind of what our experience was, and I think right now we actually in our business is turning towards B2B markets much more because we find these markets much more open too, to this kind of thinking on a mass scale.

10. What questions are open in mass individualisation research? What is going to be the next research phase?

It should be obvious to go to the market, for the point where we insert individualisation. It does need more research in terms of background, in terms of the policy making and income factors. Another approach is just to make a product and launch in the market and then see the pattern.

11. What do you recommend a person who is doing research in this domain?

I think one should so passionate about this. As I said the concept is extremely interesting. But there's a certain kind of barriers to it to actually being modular in every respect. So my advice would be for someone to work very closely with companies or entities that are working with this kind of products and within which one would want to try these things in the real world.

Also, I think, design as a whole has to be very much close to the user, as opposed to maybe some mathematical concepts. I think it's like in order to make something successful in the human centred design pipeline; one needs to be fully engaged with the user. When companies like an idea, they come up with cool design pipelines and proposals, and go ahead
and try it with customers. They might also find customers who want to try it, and then maybe they fail, but this is how they know that.

12. What one advice you would give to an ambitious entrepreneur who wants to work with this kind of product?

I think one should do it because you got to try it and fail a thousand times like Mr Dyson did.
APPENDIX E: INFORMED CONSENT FORM FOR THE INTERVIEW

INFORMED CONSENT FORM

Title of Project: Innovation toolkit for OPAP (PhD in Design Engineering)

Name of researcher: Ravi K Sikhwal

Please initial box

1. I confirm that I have read and understand the subject information sheet dated 24/12/2018 version 1 for the above study. I may keep this information sheet for my records and I have had the opportunity to ask questions which have been answered fully.

2. I understand that my participation is voluntary and I am free to withdraw, without giving any reason and without being penalised or disadvantaged in any way.

3. I understand that sections of my recorded comments and transcript text may be looked at by responsible individuals from Imperial College London. I give permission for these individuals to access this data as relevant to this and future research.

4. I am willing to have this interview audio recorded.

5. I understand that this consent form will be kept separate from the data and that the researchers will maintain my anonymity throughout the project, including in publication.

6. I agree to take part in the above study.

* Delete as appropriate

Serge Didenko
Name of Participant (Printed)

Date: 24/12/18
Signature

Ravi K Sikhwal
Name of Researcher (Printed)

Date: 24/12/18
Signature

1 copy for subject; 1 copy for researcher

Version 1
Date: 24/12/2018
Appendix F: Calculation of Objective Function for the Multi-level Optimisation of Blocks

Evaluation Index for Product Cost from equation 5.7,

\[ I_p = 1.74 - 2.8571C_p + 1.0036C_p^2 - 6.9027C_p^3 \]

Putting the value of Product Cost evaluation measure from equation 5.1 into this equation,

\[ I_p = 1.74 - 2.8571(n \times 35 + 259) + 1.0036(n \times 35 + 259)^2 - 6.9027(n \times 35 + 259)^3 \]
\[ I_p = -295953n^3 - 6.5689 \times 10^6 n^2 - 4.8601 \times 10^7 n - 1.1986 \times 10^8 \] (E.1)

Evaluation Index for Maintenance Cost from equation 5.9,

\[ I_m = 1.1 - 0.005C_m + 1.7322C_m^2 - 4.7812C_m^3 \]

Putting the value of Maintenance Cost evaluation measure from equation 5.2 into this equation,

\[ I_m = 1.1 - 0.005(n \times 20) + 1.7322(n \times 20)^2 - 4.7812(n \times 20)^3 \]
\[ I_m = -38249.6n^3 + 692.88n^2 - 0.1n + 1.1 \] (E.2)

Evaluation Index for Product Weight from equation 5.11

\[ I_w = 1.2831 + 2.9369P_w - 2.154P_w^2 + 8.5857P_w^3 \]

Putting the value of Product Weight evaluation measure from equation 5.3 into this equation,

\[ I_w = 1.2831 + 2.9369(n \times 7 + 50) - 2.154(n \times 7 + 50)^2 + 8.5857(n \times 7 + 50)^3 \]
\[ I_w = 2.9449 \times 10^3 n^3 + 6.2999 \times 10^4 n^2 + 4.4926 \times 10^5 n + 1.0679 \times 10^6 \] (E.3)

Evaluation Index for Battery Backup from equation 5.13
Putting the value of Battery Backup evaluation measure from equation 5.4 into this equation,

\[ I_b = -0.15 + 0.025P_b - 3.5489P_b^2 + 1.0516P_b^3 \]

\[ I_b = 0.0013b^3 + 1.7206b^2 + 747.289b + 108123 \]  \hspace{1cm} (E.4)

Evaluation Index for Response Time from equation 5.15

\[ I_t = 1.1 - 10P_t + 7.6218P_t^2 - 4.9725P_t^3 \]

Putting the value of Response Time evaluation measure from equation 5.5 into this equation,

\[ I_t = 1.1 - 10(n \times 0.005) + 7.6218(n \times 0.005)^2 - 4.9725(n \times 0.005)^3 \]

\[ I_t = -6.2156 \times 10^{-7}n^3 + 0.0002n^2 - 0.05n + 1.1 \]  \hspace{1cm} (E.5)

Evaluation Index for Extra Features from equation 5.17

\[ I_f = -0.0683 + 0.1489P_f + 0.0028P_f^2 + 0.0007P_f^3 \]

For this case study, middle value of this evaluation measure is taken into consideration, i.e. 5,

\[ I_f = -0.0683 + 0.1489(5) + 0.0028(5)^2 + 0.0007(5)^3 \]

\[ I_f = 0.8337 \]  \hspace{1cm} (E.6)

Evaluation Index for Ease of access from equation 5.19

\[ I_e = -0.0683 + 0.1489P_e + 0.0028P_e^2 + 0.0007P_e^3 \]

For this case study, middle value of this evaluation measure is taken into consideration, i.e. 5,
\[ I_e = -0.0683 + 0.1489(5) + 0.0028(5)^2 + 0.0007(5)^3 \]
\[ I_e = 0.0841 \] (E.7)

Putting values of different evaluation indices from equation B.1 to B.7 into equation 5.21,

\[
\text{CS}(X) = [0.7(-295953n^3 - 6.5689 \times 10^6n^2 - 4.8601 \times 10^7n - 1.1986 \times 10^8)
+ 0.6(-38249.6n^3 + 692.88n^2 - 0.1n + 1.1)
+ 0.5(2.9449 \times 10^3n^3 + 6.2999 \times 10^4n^2 + 4.4926 \times 10^5n
+ 1.0679 \times 10^6) + 0.7(0.0013b^3 + 1.7206b^2 + 747.289b + 108123)
+ 0.5(-6.2156 \times 10^{-7}n^3 + 0.0002n^2 - 0.05n + 1.1) + 0.8(0.8337)
+ 0.4(0.0841)]/(4.2)
\]

\[
\text{CS}(X) = [(-228644n^3 - 4.6631 \times 10^6n^2 - 3.3796 \times 10^7n - 8.3368 \times 10^7)
+ 0.7(0.0013b^3 + 1.7206b^2 + 747.289b + 108123)
+ 0.5(-6.2156 \times 10^{-7}n^3 + 0.0002n^2 - 0.05n + 1.1) + 0.8(0.8337)
+ 0.4(0.0841)]/(4.2)
\]

\[
\text{CS}(X) = [(-228644n^3 - 4.6631 \times 10^6n^2 - 3.3796 \times 10^7n - 8.3368 \times 10^7)
+ 0.7(0.0013b^3 + 1.7206b^2 + 747.289b + 108123)]/(4.2)
\]

\[
\text{CS}(X) = [(-228644n^3 - 4.6631 \times 10^6n^2 - 3.3796 \times 10^7n - 8.3368 \times 10^7)
+ (0.0009b^3 + 1.204b^2 + 523.102b + 75686)]/(4.2)
\]

\[
\text{CS}(X) = [-54439.04n^3 - 1.11 \times 10^6n^2 - 8.047 \times 10^6n + 0.0002b^3 + 0.2867b^2 + 124.548b + 1.983 \times 10^7]\] (E.8)