IoT technologies integration framework: A 3D printing case study

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Declaration

I declare that this document is an original work of my own authorship and that it fulfills all the requirements of the Code of Conduct and Good Practices of the Universidade de Lisboa.

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Resumo

Avanços tecnológicos estão a revolucionar indústrias a um ritmo acelerado, exigindo uma reação rápida por parte das empresas para manter a competitividade. A emergência de tecnologias de internet das coisas (IoT) contribuiu para tornar os produtos mais complexos, gerar grandes quantidades de dados e promover conhecimento baseado em dados. É crucial, para o sucesso duma empresa, realizar valor destas tecnologias.

Esta tese tem como propósito caracterizar diferentes níveis de integração tecnológica nos produtos e descrever os benefícios expectáveis pelas empresas aquando da integração de tecnologias IoT.

Para o efeito, foi elaborada uma revisão de um caso de estudo aplicado às tecnologias de impressão 3D direcionado a caracterizar as preferências dos consumidores, tecnologias IoT integradas e mudanças organizacionais requeridas. Entrevistas preliminares identificaram como valorizadas características como custo, qualidade, velocidade de impressão, conectividade e facilidade de uso. Tecnologias como controlo remoto, produção através da cloud, diversos sensores e uso de câmaras para a deteção de erros revelaram permitir às organizações melhorar o conhecimento e controle do processo, a sua flexibilidade, precisão, qualidade, eficiência, robustez e tomar decisões mais informadas.

O trabalho desenvolvido serve de um mapa estratégico de integração tecnológica. Cinco níveis diferentes foram identificados, cada um indicando o conhecimento técnico específico, as mudanças organizacionais, integrações de tecnologia necessárias e os benefícios expectáveis em cada nível. Com esta ferramenta, empresas podem identificar os diferentes níveis de conectividade e guiar desenvolvimentos tecnológicos nos produtos. Permite gerar um maior conhecimento sobre o consumidor e melhorar a tomada de decisão através dos dados gerados.

Palavras-chave: desenvolvimento do produto, Internet das coisas, indústria 4.0, impressão 3D

Abstract

The rapidly changing technological environment is requiring organisations to quickly react to remain competitive. Emerging Internet of Things (IoT) technologies contributed to increase the product's complexity, gather large amounts of data and allow data-driven insights. It is crucial, for the company's success, to realize value from these technologies.

This thesis aims to characterize multiple levels of technological integration into products and describe the benefits companies can expect when connecting devices.

For this purpose, it was conducted an analysis of a case study on 3D printing technologies aimed to characterize consumer preferences, existing IoT technologies integrated, and organisational changes required. Preliminary interviews conducted with consumers identified as valuable characteristics like cost, quality, speed, connectivity, and ease of use. Technologies like remote monitoring, cloud manufacturing, sensor installation and camera for error detection are a part of 3D printing models.

The developed framework serves as a strategic technology roadmap for IoT integration. Five different levels were defined, from lower end models to fully connected devices that highly improve processes. This helps companies in improving process knowledge, flexibility, precision, quality, reliability, efficiency, and make more informed decision-making. Ultimately it assists to comprehend the requirements for advancing to next technological integration levels and what benefits to expect. It enables organisations to make decisions based on data gathered from their devices and better understand consumer perspective, thus positioning their products strategically in the market. Furthermore, it encourages an iterative methodology that promotes a flexible response to the changing consumer needs and the technological improvements.

Keywords: product development, Internet of Things, Industry 4.0, 3D printing

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List of Acronyms

CAD	Computer Aided Design
IoT	Internet of Things
NPD	New Product Development

1. Introduction

In this thesis it is developed a framework targeted at industrial companies interested in integrating Internet of Things (IoT) technologies in an industrial setting. Based on consumer-centric focus, technological integration, and organisational changes the framework comprises a comprehensive perspective of the product development field. The framework is developed through a review of literature and the analysis of case study being further generalised to widen its applicability. This aligns with previous research in the field of product development within an industrial setting. The integration of IoT technology and a market directed at consumer focus and intensive knowledge processes underscores the need for the development of this work.

1.1 Motivation

The field of product development is currently undergoing a transformation fuelled by modern technologies. Shaped by historical changes in manufacturing paradigms—from individualized production to mass production and the era of mass customization—the complexity of products has evolved significantly [1].

The current manufacturing paradigm is characterized by information-intensive processes, customer-centric products driven by data gathering and analytical insights, and the Industry 4.0 revolution, making the development process more complex. Even more, the product development methodologies have shifted according to evolution of operations management paradigms, following the dynamic nature of the market, which emphasizes customer needs and intensive knowledge processes, requiring user engagement in the development process. These changes in the market lead to need of adopting flexible methodologies, like agile, which are crucial to face the constant changing market demands and rapid technological evolution [2].

Furthermore, products now have mechanical, electronic, and software features, including services and connectivity which require multiple technical expertise to operate within a flexible, multifunctional setting. This is a critical change in a company’s environment when dealing with technological integration, where multiple knowledge areas are required to contribute to a more consolidated perspective in the development of a task [3].

Industry 4.0 and the IoT brought a wide range of new features offering seamless connectivity and data-driven insights into the process of product development. To make use of this data is crucial to gain competitive advantage in a consumer-focused market. Thus, extracting value from the data gathered should be a part of a company’s strategic development, by connecting devices and create valuable insights towards more sustainable processes [3].

However, realizing value from this data represents a challenge as it requires a holistic approach containing strategic development, organizational changes, technological integration, and alignment with customer expectations [3]. The framework developed aims to help organisations to realise the potential of these technologies by adopting these steps and acquire a competitive advantage in the fast-changing field of product development.

Literature on product development frequently lacks practical specificity and relevance and favours theoretical frameworks. Despite their value, technology roadmaps frequently lack integrated and comprehensive perspectives as it offers generic guidelines but lack case-specific and useful information for framework development [4].

The research carries out a literature review of product development, involving the evolution of production paradigms, changes in management methodologies and current technological market demands. This establishes the foundations for the case study analysis focusing on technological integration, product development and organisational changes.

This thesis addresses a relevant gap in the literature by helping companies to navigate through their technological journey by developing an integrated approach derived from a case study analysis which ensures practical applicability. It also covers the growing market trend for knowledge integration in processes in the various engineering fields, especially considering the evolving nature of technology, mechatronic and software-hardware products.

This study is driven by the need for companies to quickly adapt to the fast-paced technological landscape which require adaptable processes and organisational structures, so that companies can remain competitive. Furthermore, it recognizes the requirement for a comprehensive, multi-field perspective that is crucial in effectively integrating technological changes, particularly in an industrial setting, where frameworks support managerial decisions to further improve the manufacturing process.

1.2 Objectives

The primary objective of this body of work is to develop a comprehensive framework that classifies products into distinct technological levels, offering a structured methodology and guide for bettering product connectivity. This framework is designed to assist companies in the implementation of technological advancements in industries equipment.

The study responds to two research questions:

1. What benefits do companies obtain from integrating IoT technologies into their products?
   This question intends to describe what companies can expect when implementing technological changes in their products.
2. What are the requirements for companies to improve their products’ connectivity?
   This question intends to reveal the technological integration, organisational change and expertise required to enhance the products’ connectivity.

By interlinking both answers to these questions, companies can effectively balance the benefits expected against the requirements to increase their products’ connectivity.

Based in the 3D printing industry, the case study seeks to closely relate to the industrial production setting and guarantee the development practical and valuable insights.

1.3 Thesis Structure

This thesis begins with a bibliographic review of the topics of interest required to better understand the developed work, followed by a case study analysis from which the framework proposed is generalised.

Chapter 2 conducts a literature review that describes the evolution of production paradigms, product development methodologies, and project management techniques. This reveals how the increase in efficiency of production and product development tasks have contributed to the state of the current production paradigm. It is explored what are the key factors to ensure product development success. The literature also describes the role of agile methodologies in the manufacturing sector and product development processes. The impact of multifunctional teams and customer involvement in product development is highlighted. Furthermore, IoT technologies and technology roadmap methodologies are reviewed, and contribute to the understanding of the technological aspects of the research. Additionally, it provides an overview of big data to guide the study's data-driven approach. The literature review also includes an analysis to different 3D printing technologies and their impact in product development.

The third chapter describes the approach used in the case study.

Chapter 4 includes the results and discussion from the analysis to the case study. The following chapters explore different areas of the case study. The interview chapter describes the qualitative research results, providing insights from users of 3D printing machines. Participants stated their background knowledge relating this technology and their experiences, their knowledge on the technological developments, the impact of 3D printers on their work and future expectations for this technology.

Subsequent chapters analyse different customer groups for 3D printing machines, highlighting preferences based on intended use and desirable features. Connectivity options identified in the models analysed are examined, exploring their benefits and impact on product efficiency. Organizational changes required for implementing technological integration are detailed, outlining required knowledge areas and steps for each level of connectivity. Finally, the framework is consolidated, considering all these diverse areas to create a structured tool for technological integration, enabling the assessment of the technological level of a product.

On chapter 5 the final conclusions regarding the developed work are analysed. Considerations on impact and future work are also discussed.

2. Literature Review

The literature review analyses the work developed in the different fields addressed in this thesis, as presented in **Figure 1**. Starting by the review of the product development field and different particularities relevant to understanding the status of manufacturing processes. The project management field review addresses different agile methodologies and the organisational restructuring of an agile setting. Industry 4.0 introduces the technological aspect of the review. Lastly, 3D printing technologies relevant to this study are reviewed.

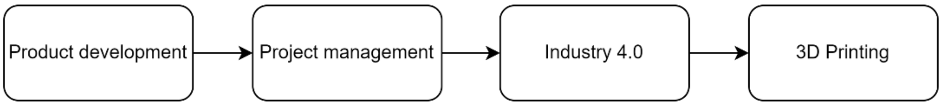

Figure 1. Literature review diagram

2.1 Product Development

The product development process has a complex and extensive history across many centuries and different industries. It started from the development of basic tools to advanced technological products, through human progress and innovation. To understand the evolution of product development frameworks is crucial to comprehend the progression of manufacturing paradigms [5]–[7]. The stage-gate methodologies describe the tasks of a sequential product development process. Multiple studies contributed to the enhancement of these techniques and perfecting processes. These studies are reviewed in the product development process methodologies [2], [5]. New product development models address product development of new products, encouraging creativity. These methodologies provide different focus areas from which different benefits are targeted. The key factors for a successful product development is a developed area of study with crucial relevance for the development of a tool in this field area [1]. The trends and gaps from the revised literature contribute to fully comprehend the current state of the work developed in the product development field.

2.1.1 Production Paradigms

Product manufacturing has started from the early days of human civilization when manual labour was used to create simple products. As time passed, the manufacturing process became more structured, moving from small-scale industries to large factories that required high investment and focused on producing high volumes of products.

In the initial phases of product development, a single worker was responsible for creating products from beginning to end, possessing the entire process knowledge. However, with the progression in production methodologies, specialisation and task division emerged allowing for a more flexible production structure [6].

When discussing the progression of manufacturing systems, Mourtizis and Doukas identified three distinct manufacturing paradigms that have developed in response to changes in their respective operating environments [7].

Craft shops that employ skilled artisans that represent the traditional manufacturing methods, where products are meticulously crafted by hand. Each item is typically one-of-a-kind and personalised. The emergence of craft shops marked the beginning of product development, with skilled craftsmen utilising their expertise and craftsmanship to create unique and customised products [7]–[9].

Interconnected Industrial systems that use automation represent the industry era where machinery and automation are implemented on a large scale to achieve mass production. These systems are connected to streamline production processes and create standardised products. During this period, various management techniques surged to enhance and optimise the manufacturing process [10], [11].

Furthermore, the third identified paradigm, the post-industrial enterprises are characterised by flexible resources and reliance on information intensive processes. This current paradigm values the production of knowledge and data collection as it is essential for a successful strategic development [7]. Furthermore, Jack Hu distinguished several distinct periods for production paradigms, in an article regarding the evolution of manufacturing paradigms (**Figure 2**).

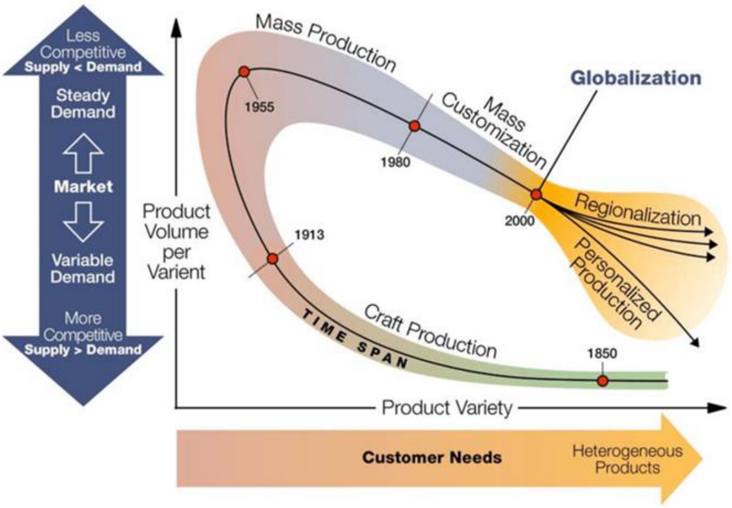

Figure 2. Changes in manufacturing paradigms [12].

The relationship between product variety and volume is depicted in the figure, along with the evolution of the different paradigms. Usually, volume and variety are inversely related, more diversity often leads to decreased volume due to extra time, effort, and processes required. High-volume production boosts efficiency and cuts costs through standardisation of processes and economies of scale. Usually custom items are more complex, require flexible systems and higher costs. Mass customization and flexible manufacturing techniques made it possible to produce a wider range of products without significantly reducing output or efficiency. Personalised production is still an objective for many manufacturing companies that aim to enhance their processes [12].

Craft production represents the early stages in product development, where no production system was in use and products were produced at a high cost within the same geographical area for individual customers [8], [9]. There were no defined product development processes, only simple task execution by a craftsman [6]. In the early to mid-20th century, mass production arose, the primary concern was to produce large amounts of the same product, achieving low prices from economies of scale and high productivity. During this period, there was a focus on improving the production phase of product development by optimising operations. The production started to be divided into different blocks of actions in a simplified way, so that any worker could perform these simple tasks, thus diminishing costs [6]–[8]. Frederick Taylor's scientific management theory increased labour productivity and process efficiency. It structured production lines by breaking down tasks and eliminating unnecessary movement, creating machine-like routines for efficient work [6], [10].

Henry Ford introduced mass production with standardised goods on assembly lines, using dedicated machinery and semi-skilled labour, drifting away from sequential production. Components were made individually and assembled later, focusing on simplicity and standardisation for high-volume production across different models [10], [11].

To ensure products were developed systematically, a process was established that covers the entire product development lifecycle from idea conceptualization to production [5]–[7]. During this era, the stage-gate process approach was introduced, which brought structure and discipline to product development. The stage-gate process divided product development into different stages, which will be further discussed later in the literature review. Doukas and Mourtizis further add the American production paradigm, between the craft and mass production systems, to emphasise the inefficiencies of the early American production [7].

Many project management techniques were developed to enhance processes, as well as advancements in automation technologies and changes in management paradigms, ultimately resulting on a more efficient product development workflow. The Toyota production system brought Lean and continuous improvement techniques to manufacturing. It aimed to enhance customer value and eliminate process waste, this idea quickly spread among diverse industries, lowering operational expenses [8]. It also encouraged cooperation by collaborating with suppliers to outsource simpler parts, increasing transparency of production costs and quality along the supply chain. The just-in-time system lowered inventory expenses by delivering products when needed, benefiting both manufacturers and suppliers [13]. This supply chain insight improved process flexibility, enabling responses to market demands for variety and quality while keeping costs low. Management techniques such as delayed differentiation, product modularity and reconfigurable manufacturing system (**Figure 3**) contributed to the increase of process flexibility, allowing higher customization [9], [13]. Ahmad et al. discovered in 2010 that attaining competitiveness required functional coordination amongst designs. More related to competitiveness than product modularity was the ability to structurally manage all aspects of production [14].

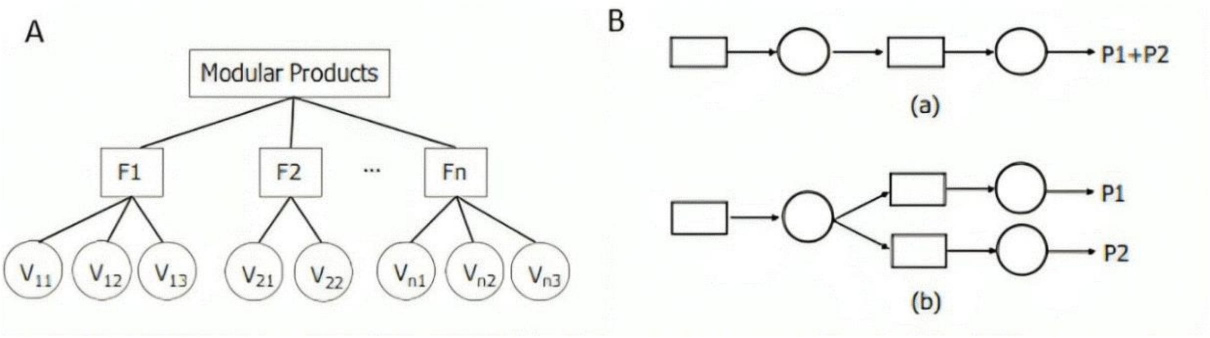

Figure 3. (A) Product Family Architecture and (B) Manufacturing system configuration: a) mixed model assembly, b) configuration with differentiation.

As products became more complex, including mechanical features, electronic components, complementary services and software integration, a wider knowledge area was needed to fully develop products. Moreover, there was an increased focus on “product life-cycle issues that include product life cycle management, end-of-life treatments, and different forms of added value generation such as service and product-service systems due to growing concerns about the global environment.” [6]. Thus, there was a wider spectrum of issues regarding product development that required a deeper analysis through different areas of concern. Product data management, product life cycle management, supply chain management, value chain management and customer relation management were integrated in product development processes to build more comprehensive and solid approaches to product development. The integration of these techniques and management styles in product development processes, as well as, multi-disciplinary teams, allowed product development processes to run more smoothly and improve decision-making capabilities [8].

In recent years, the rise of customer-centric and agile approaches has transformed product development even further. With increased competition and evolving consumer expectations, businesses have shifted their focus from mass production to customization and personalization. This created a highly competitive environment that requires high performance, flexibility, and innovativeness from product development tasks for companies to strive [12].

The introduction of computers and digital technology in the late 20th century revolutionised product development once again. Computer-aided design (CAD) software made it easier to create and visualise product designs, accelerating the prototyping phase. The use of simulations and virtual testing also became more prevalent, reducing the reliance on physical prototypes and minimising costs. Moreover, communication and collaboration among team members improved with the emergence of project management software and online platforms. The focus shifted into creating a centred information database to be used in the different stages of product development to improve productivity, cost, and quality via data integration [6].

These developments were especially relevant to the performance of product development design phase, which has been a main research field for many years [15]. CAD software is a crucial tool to product development design that deals with geometric models and parametrization of the product. Because of the complexity of design work, interaction between the designer and the CAD system is essential for achieving effective and efficient outcomes. Recent literature considers managing design information to be an important problem in CAD systems and addresses it by proposing frameworks to improve the spread of design information and intention, of each design phase, into the downstream process [15], [16]. Additive manufacturing plays an important role in product customization and prototyping. The application of additive manufacturing in producing medical devices, electronics and industrial goods is growing. 3D printing technologies developments are lowering costs and time required to create products [16], [17].

As the market became global, access to different services and specialised companies allowed enterprises to outsource part of its tasks and focus on core competencies that increase value to the product. Supply chain managers aimed to increase the supply chain flexibility and the system reliability by creating strategic alliances and leveraging its global network [9], [13]. These “alliances are both pathways for the exchange of resources and signals that convey social status and recognition.” In fact, studies have shown that strategic alliances can improve performance and are highly advantageous even when they fail to achieve their goals [18]. Partnerships create knowledge sharing and a novel environment that favours innovative initiatives, towards new product development (NPD) and process development tools [19].

Some limitations to mass customization are pointed out in a 2017 study by Wang. et all. Customers do not fully engage in the design phase, designers have predefined combinations for the customise product, the notion of mass customization is insufficient to meet individual needs and is incapable of delivering individualised services and commodities. These challenges hinder the capacity of companies to achieve a mass customization and, even more, a personalized production paradigm [20]. Another outlook on production paradigms relates to customer involvement, volume, and costs, as describe in **Figure 4**.

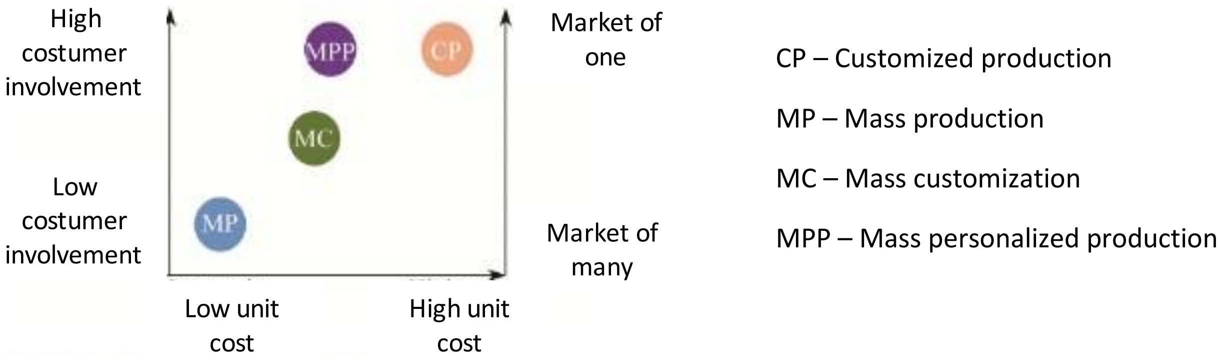

Figure 4. Taxonomy of paradigms of production

Less interaction from the client results in more mass-produced goods that can achieve economies of scale and offer lower pricing. Customization typically generates higher cost products.

In a market of one perspective, the customer should play an essential part in the product development design phase, as the final product is specifically customised to the consumer’s preferences and individual needs. Customers collaborate with manufacturers to create innovative products with increased efficacy and value to the consumer [8].

The transition from mass customization to a mass personalization paradigm was imposed by several factors, identified in a 2007 theoretical research by Kumar: Market pressure, changes in IT capabilities enabling customer integration into product design, the evolution of customer relationship management as a strategy, improvements in resource planning, data warehousing, and data mining. The introduction to industry 4.0 technology developments allowed these factors to converge into a personalised production paradigm [21]. The internet's far-reaching presence, software incorporation in electronic devices, advanced computing systems and emerging responsive manufacturing systems, such as additive manufacturing, created a highly flexible production and design environment with increased product variety and relatively low unit cost, as shown in **Figure 4**.

Gunasekaran and Ngai synthesised the evolution of operations management paradigms considering the changes in the surrounding market and society environments (**Table 1**) [9].

Table 1. Evolution of Operations management (reproduced from [9])

Period	Objectives	Strategies / Technologies
Beginning	Individual customer requirements	Craftsman and artesian production
Post World War II	Immense demand for costumer products	Total quality management, just in time, transfer line production system, Frederick Taylor's scientific management theory
1975-1985	Medium volume and medium variety	Quantitative Risk Management, Computer-Integrated Manufacturing
1985-1995	Cost reduction, high variety, and low volume	Lean, agile, and physically distributed enterprise environments
1995-2010	Higher variety and very low volume	Outsourcing, global manufacturing and market, agile, Internet-enabled supply chain management (SCM), Third party logistics
2010-	Global individualized products and services	Global SCM, virtual enterprise, sustainability

This table briefly resumes the production objectives, required by the market, and technologies used to fulfil those demands at each period. Currently, there is a strong focus on managing and collecting data to integrate in production, marketing, and product development systems to improve processes, increase the general knowledge of the market, the product, and support decision-making. Increasing the connectivity between products and to the web is a growing trend to collect data and offer new services more effectively. A lot of research is being conducted in this direction; these new trends will be further explored in the IoT section.

To comprehend the current state of product development processes, it is essential to understand this perspective on production paradigms. This makes it easier to draw a link between product complexity, current manufacturing systems, and management frameworks, which provides a basis for the rest of this review.

2.1.2 Product development process methodologies

Karl T. Ulrich and Steven D. Eppinger's book on product development is a widely used resource [5]. It offers a comprehensive overview of the product development cycle, ranging from the idea creation to their successful market launch, featuring a range of tools, case studies, and techniques for achieving innovation success. According to them, the literature can be organised into different common perspectives: marketing, organisations, engineering design, and operations management. The marketing perspective helps identify consumer preferences and define the value of different product features. Organisational perspective literature is focused on the surrounding environment in which a firm develops its work. Engineering design focuses on the technical part of product design process and development. Operations management aims to improve operations efficiency by reducing costs, lead times, increasing capacity in use and service level. These different perspectives summarise the main points of view on how researchers' approach research [2], [17]. This review tackles these different perspectives as we aim to understand how organisations, consumers, design, and management can impact products and product development processes.

Early product development studies were concerned with the structure of the development process. This process refers to the stages taken by a company to create, design, and market a product. As products became more complex, so did their development process, the range of technical issues, the wider areas of knowledge required, and organisational structures employed over the life of a product development [1], [5]. As reviewed in the evolution of production paradigms, the developments in production processes, the increased integration of technology and electronics in products, and market environment changes lead to more complex products and product development processes. "Product definition, development, launch and project management methodologies are highly contingent on the market uncertainty and other environmental characteristics" [17].

The typical product development process is represented by a sequential model, from idea generation to product launch. This process appeared naturally from the analysis of product development projects, as often, the same sequential tasks were performed every time a project was conducted [5]. Robert Cooper, one of the main researchers on the product development's field, created a waterfall process called stage-gate, that presented the 5 necessary steps to develop a product (**Figure 5**) [22].

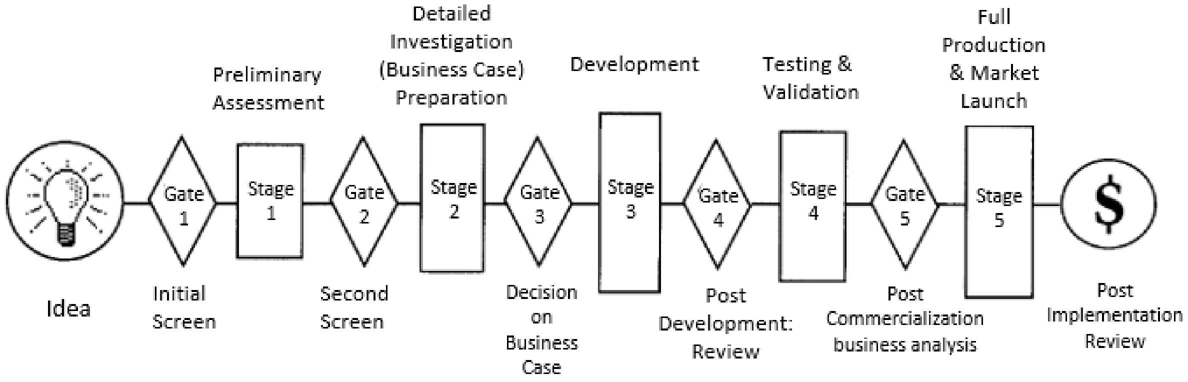

Figure 5. Stage-Gate Process [22]

Each development phase (stage), which depicts a task performed in the process, is followed by a review (gate) of that activity to confirm its completion and checks a set of criteria necessary for the product to proceed with the process [5], [22]. This product development framework can be seen as a guideline to generic development of projects that follow similar processes. The field of product development process modelling has reached its maturity, with little recent research towards developing new models but instead adapting processes and management techniques [1].

In his research Cooper analysed different failure and success of product developments by each of its stages. It was found that high execution quality in early activities is prevalent in products that succeeded. Thus, planning is of extreme importance to ensure the quality of the process and commercial success of products [22].

Along the product development process, making changes gets increasingly costlier in development tasks as it reaches the final product [22]. Well defined strategy and planned decisions in the early stages of product development leads to a smoother development process. Preliminary market and technical analysis are crucial to source out information that improves decision making through the workflow. Mitigation and adaptation, of earlier mistakes, during later phases of the process are risky procedures that highly increase costs, lead time and the amount of effort needed to complete the tasks [5], [17], [22]. Cooper also emphasises the importance of defining specific criteria to ensure that projects are evaluated fairly and consistently throughout the process, screening possible failures and guaranteeing the success of the committed projects developed. Establishing these parameters prevents gut decisions to overlap the defined criteria and create a biased evaluation procedure [22], [23].

The product development model suffered multiple adaptations, ranging from specific case study versions to more generic models [5], [17]. Tyco developed their own product development model based on their type of product, how it is produced, commercialised and how it creates value to the customer. Their idea generation comes from perceived market needs (market pull), so the process to develop new products is naturally different from a company which develops products based on new technology advancements (technology push) or increments innovation to already existing products.

Takeuchi and Nonaka conducted an analysis through product development corporate practices and reviewed the holistic method companies use. They analysed different American and Japanese companies to find that projects were passed along within a large multi-functional team as the process moved through the different stages. Opposing to moving the project sequentially through the development phases. This translated into different characteristics, such as self-organising project teams and overlapping development phases, that produced a fast flexible process [24]. Such is presented in **Figure 6**.

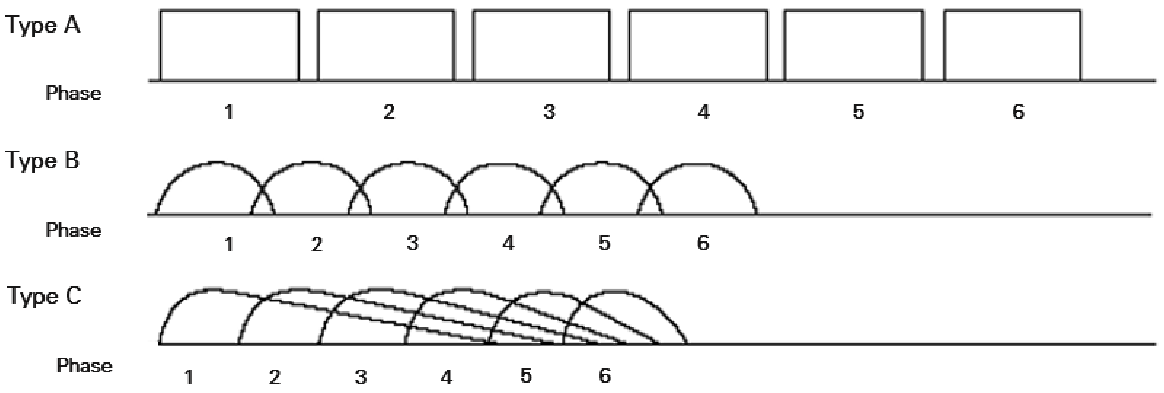

Figure 6. Sequential (A) vs Overlapping (B and C) phases of development [24]

For businesses looking to create new goods rapidly and flexibly, this strategy is key. Changing from a linear to an integrated and overlapping approach, trial and error is encouraged. It promotes new ways of learning and thinking across all levels and departments of the organisation. Additionally, this model influences the organisational structure of a firm, working towards a more flexible environment. Organisations can benefit from this working method by loosening some of the rigidities that have grown through time [5], [24].

Taking a design-oriented perspective, Ulrich, K. T. and Eppinger, in their book, examined different variants of the processes according to “the unique context of the firm and the challenges of any specific project” and specified the different characteristics of the identified types. In **Figure 7** are presented two variations of the generic product development process. A spiral product development process (b) enables the iterative repetition of design, build and test activities. This type of process is commonly used to develop digital and quick-build products through agile management methods. In a complex system (c), the product is split into multiple modular products to ease the activities complexity [5].

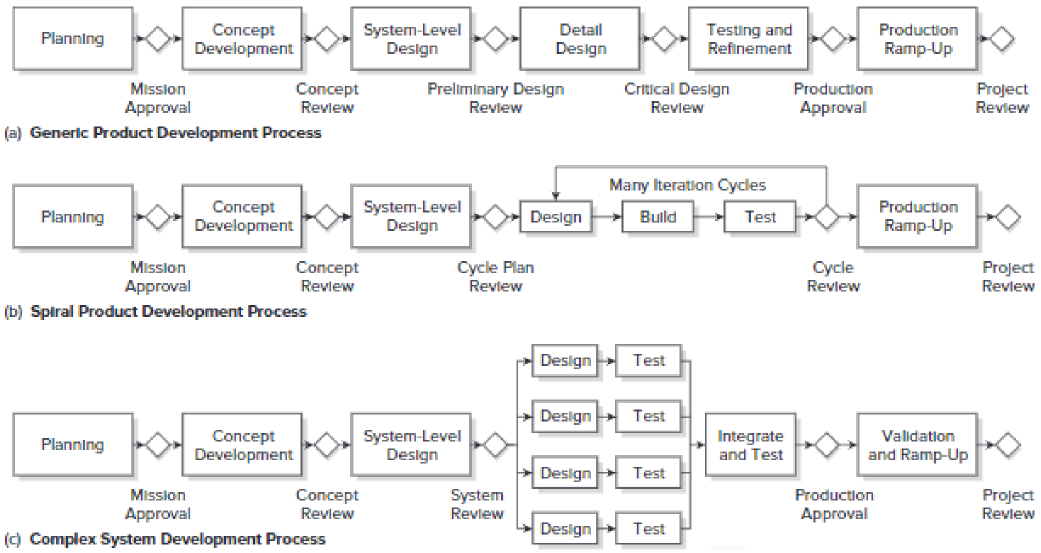

Figure 7. Generic and Variations of product development processes

The production of large-scale products comprises many interacting subparts and benefits from individuality, to a certain degree, dealing with each component separately to reduce the systems' complexity [5]. Working with modular architecture also allows standardised subsystems to be shared across production lines and outsourced to more specialised companies. It increases the process flexibility, as components can be produced simultaneously in parallel. Research also shows benefits to modular architecture in terms of decreasing costs and improving development lead times [25].

These findings revealed the benefits of iterative methods in product development processes, leading to the development of agile methodologies that will be described on the organisational overview of the product development process.

2.1.3 New product development

The new product development models (NPD) reflect adaptations of the typical product development models to better suit the development of new products. These frameworks, which guide businesses as they create and launch new products or services, facilitate creativity, speed up the development process, and raise success rates. Some frameworks that can be used as guidelines to develop new products are represented on **Table 2**, as seen below.

Table 2. Examples of methodologies used in new product development

Model	Focus	Description	Benefits
Design thinking	Consumer	Consumer centred approach that emphasises empathy, creativity & iterative problem-solving. It entails understanding user's perspective, defining the issue, discovering solutions, testing, prototyping and applying the solution	Addresses Consumer needs effectively
Open Innovation	Partnerships	According to this model, business shouldn't just rely on their own internal resources to innovate. To speed up their NPD process, they must look for outside ideas, technologies & partnerships	Encourages collaboration & access to innovation
Lean startup	Efficiency	Advocates building a minimum viable product (MVP) quickly and putting it through market testing to get consumer feedback. The product is then iterated & improvised using it	Allows low-cost market testing
Scrum	Flexibility	Iterative development of products that divides the work into smaller manageable tasks in short timeframes	Increases flexibility & adaptability

The choice of NPD model depends on the industry, market conditions, organisational culture, and project characteristics. Companies often combine these models to create a process that aligns with their unique needs and goals.

W. Veryzer (1998) analysed the process of product development for discontinuous innovation. Products that involve radical departures from existent products or a revolutionary turn in the logical extension of a product are characterised by discontinuous innovation. This type of process differs from that of continuous new products, which tends to be more exploratory and less consumer driven. The developed model resulted from the analysis of firm's practices that established successful products from discontinuous innovation. This product development model reflects the inherently messier process this type of products go through, there is a high degree of uncertainty, especially in earlier stages, and a lack of formal structure as looseness is required to fully explore innovative solutions [26].

The evaluation of the success of a product development process is related to product market success. "From the perspective of the investors in a for-profit enterprise, successful product development results in products that can be produced and sold profitably" [1]. Product quality and cost, development time and capability are dimensions, directly related to profit, used to measure the process performance. The extent to which the process succeeds in generating items that fulfil customer needs is significant for the company in determining the success of new products [27]. In fact, "the economic success of most firms depends on their ability to identify the needs of customers and to quickly create products that meet these needs and can be produced at low cost." [1].

2.1.4 Success factors

Product development researchers have extensively studied the factors that influence the success or failure of new goods. This area of study aims to identify the best practices to apply on product development to assure commercial success.

The critical success identified in earlier studies still hold relevance to this day. Poolton, J., & Barclay, I. (1998) analysed past research and identified common product development success factors. During the development phase of a product, they found it was beneficial to revisit the study of new developments, taking into account any issues identified during this stage. Testing and validation should be conducted as early as possible in the development process to validate initial prototypes before adding additional features to the product and retesting. Additionally, multiple functional departments should be involved in each stage of the development process to create a robust solution, given the complexity involved in producing and marketing a product.

Multiple general success factors were identified, and general practices were derived to achieve success (**Figure 8**) [23].

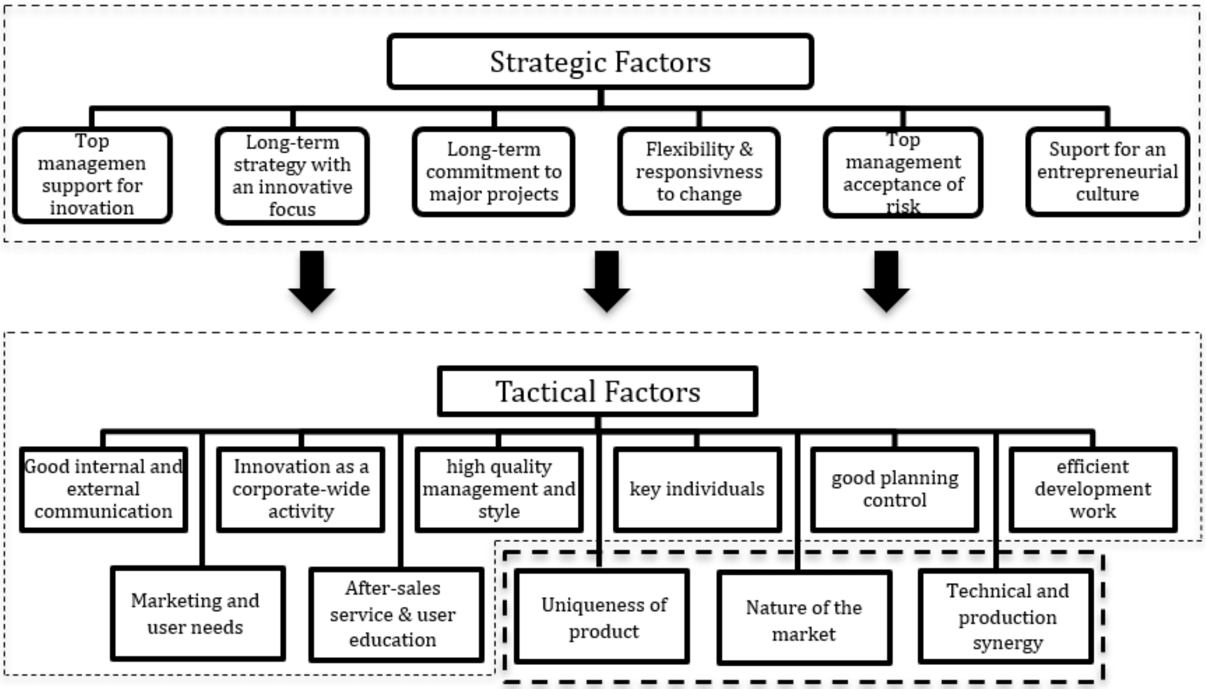

Figure 8. Main variables associated with development success [22]

Top management interest and efforts in conducting product development tasks are highlighted in the literature as crucial to the process success. Senior management involvement is necessary along the project development [1], [5], [23], [28]. Customer collaboration highly increases product success, the customer input should be considered from the idea generation phase until the end. Resources can be squandered when overlooking the customer's concerns [27], [28]. Building a strong market research and analysis favours product development planning and profitability. A well-built strategy has a high positive impact in the product development process [23], [28]. Overall, the identified factors revealed that a flexible workflow resulted in beneficial outcomes in the development process [23].

However, despite these efforts to improve new product development mechanisms, with the increasing literature and methodologies produced, the failure rate of new products remained constant, and many product development projects failed [23], [27]. McKinsey reported that more than 50% of all product launches fail to meet business goals [29]. Poolton and Barclay concluded, in their 1998 study, that key success factors failed to be translated into actionable recommendations. Project leaders still rely on experience and "gut-feeling" in the decision making, which has been exacerbated by research that tends to be theory-driven rather than applications-based [23], [28]. This represents the difficulty in addressing in a general manner a complex process that is highly interchangeable between companies. Also, it is known that the dynamic entrepreneurial environment and the high uncertainty in developing new products leads to difficulties for companies to achieve commercial success against fierce competition.

Hanna et al. (1995) assessed the differences between business and consumer companies' product development practices and company organisational structure towards product development processes. This study, based on a survey responded by 147 representatives of business and consumer companies, revealed no predominant use of a specific structure to guide new product development processes [28].

Notwithstanding, top management support in the process shown to be more relevant to product success than following a structured product development process.

Another relevant aspect brought up in this study is how these different types of companies generate ideas. Business companies place heavier reliance on customers as a source of ideas, as B2B companies usually develop specifically tailored solutions. Even though studies found suppliers to be a significant source of innovation, this research found that only 32% of the companies analysed resort to this idea source [28]. Partnering up and building strong relationships with suppliers increases the product's chances of success.

2.1.5 Trends and Gaps

Product development is a pivotal function of a firm. The process is crucial to ensure quality of the tasks performed, coordinate team members, supply a planning structure to the overall development, function as a management tool for assessing the performance of an ongoing development effort and helps identify improvement opportunities as it reviews the organisation's workflow of the project [5].

Existing research has established that high performance in the product development process leads to successful products, thus increasing companies' competitiveness. Product developments highly contribute to the companies' growth and technology advancements. Moreover, a 1980's study reported growth in the percentage that new products represent of the total companies' profits [24]. McKinsey denoted that, in 2011, 25% of all profits across industries came from new product launches [29]. In fact, most businesses' long-term viability depends on their capacity to deliver a steady supply of new items to both present and potential clients.

It has been denoted by the scientific community that research around product development is inclined to focus on theoretical frameworks [23], [28]. It is common that literature includes reviews, developing guidelines, criteria etc. that can be applied to different environments, making it less practical and process specific. Although theoretical publications offer a wider range of applications and stronger foundation to the product development research, it diminishes its practical relevance.

Poolton, and Barclay (1998) reviewed research associated with successful new product developments and concluded that research thrives in regions with strong representational schemes [23]. The development of parametric representations leads to large bodies of work and high applicability in diverse environments, small entrepreneurial firms, and varied industries, which helps to increase the relevance of the development literature [23]. The application of the theoretical work in case studies results into practical research with highly relevant empirical results and managerial implications. Research flourishes when driven by the demands of industrial practice, as product development is a business function, and so most product development knowledge is useless outside of the commercial realm. Thus, the need for industrial practice should be a strong motivator to accomplish more fruitful work [17], [23].

To reinforce this, Krishnan and Ulrich examined the literature regarding fundamental decisions made during each task of the product development process and across different dimensions. An opportunity for effective research arises when considering the environment for which research seems to be more rewarding and useful. The construction of representational schemes derived from practical case studies inside a commercial realm that focus on integrating data into the product development process [17].

From the reviewed evolution of the production paradigms, it was denoted that products are getting more complex and multi-disciplinary, product development processes are increasingly focusing on consumer integration, data and connectivity.

Tomiyama and Meijer (2006) concluded that “the next generation product development should focus more on knowledge-centred integration due to the increasing importance of knowledge intensive products and product-service systems that require a wide variety of product life cycle knowledge.” [6]. Including a wider range of engineering fields to develop tasks and integrating different activities that share common tools or processes are different types of knowledge integration suggested in their study. This is a growing trend that is evolving, beyond mechatronic characteristics, into the software and hardware combination of products [17].

In this regard, recent product development research has been concerned with integrating collected data into product development processes. Data regarding consumer product use, developing phase, product performance etc. Introducing frameworks that work around the integration of product knowledge and customer insights into the early process phases helps to make better suiting decisions, develop higher quality products and increase the process flexibility [6], [17]. Thus, combining product data created during product use phase into the product development process is crucial to increase decision making capabilities and the product success.

It is certainly relevant to explore this area in light of the new technological developments and data collection trends. The trends and gaps referred are summarised below.

Gaps:

- Literature lacks practical specificity and significance.
- Need for research driven by industrial settings.

Trends:

- Exploration of comprehensive frameworks that promote knowledge-centred integration.
- Integrating multiple engineering perspectives and multi-disciplinarity into tasks.
- Increasing focus on consumer, data, and connectivity integration into processes.

2.2 Project Management

Project management is a multidisciplinary field of study that presents methods for planning and executing out a development project. Project management research towards product development focuses on developing management methods to coordinate resources and improve task performance during the process [17]. Agile methodologies greatly influenced product development tasks promoting flexibility and are crucial for the development success of products. The introduction of flexible work methods encourages collaboration and a multifunctional setting for the organisational structure. Furthermore, these methodologies align with the customer-centric trend and offer some approaches to foster the use of costumer's insights in product development [30]

2.2.1 Agile methodologies

Agile methodologies have transformed product development. This methodology places a strong emphasis on flexibility, teamwork, and quick iteration, empowering teams to quickly produce high-quality products that live up to consumer expectations. Agile has gained popularity across a variety of industries especially in technology industries, due to its ability to react quickly to altering needs and to deliver value frequently and early [31]. Agile project development approaches take an incremental and iterative approach, as presented in **Figure 9**.

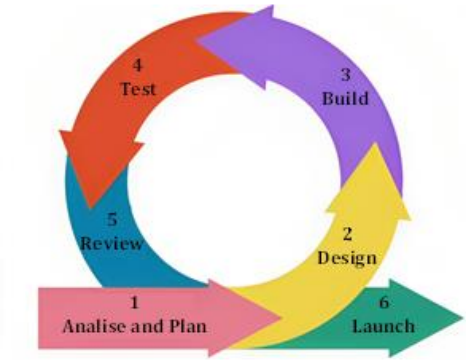

Figure 9. Agile methodologies common diagram (reproduced from [29])

This moves away from the conventional sequential method and adopts iterative phases that include all the processes required to finish the project. Iterative steps are quite advantageous in product development processes, as was already mentioned. While agile approaches are frequently used in IT projects, traditional businesses that have traditionally used stage-gate methodologies are also incorporating them into the production of physical products. The Gantt chart is an essential tool to project management methodologies, created by Henry Gantt, as an effective way to manage production plans and projects [31]–[34].

Robert Cooper (2017) emphasised the value of resource management for effective innovation [32]. Effective resource management is facilitated by agile approaches. Furthermore, agile encourages the development team to divide work into manageable units called sprints rather than following a linear and sequential procedure. A functional component of the product is built, tested, and reviewed throughout each sprint, which lasts for a few weeks on average. With this iterative process, the team can continuously evaluate and improve the product, making it more durable and flexible to meet changing needs [31]–[34].

Cooper (2016) explored the benefits of a hybrid Agile-Stage-Gate model by integrating agile methodologies into stage-gate processes. The proposed model includes performing sprints for each development phase of a typical stage-gate approach creating a continuous review of the process so it could be improved in the light of new findings, in **Figure 10.**

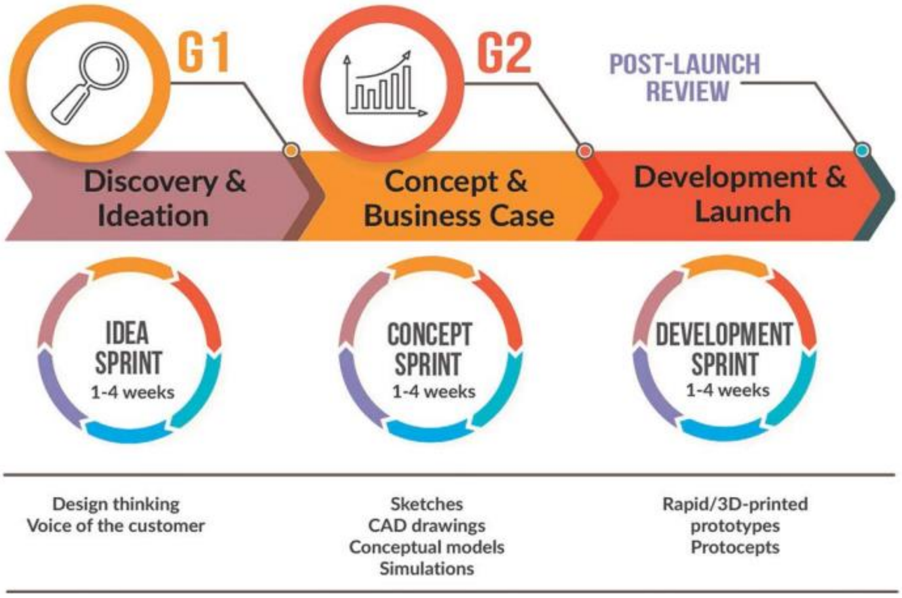

Figure 10. Agile-Stage-Gate methodology [35]

The outcomes of this study, which concentrated on a hardware project context, exceeded expectations and resulted in a significant development speed gain of 30%. Additionally, the concept improved employee happiness and motivation. A component of agile technique called Scrum was effective at closing knowledge gaps, especially in the early phases of projects.

Businesses are increasingly integrating Scrum with the gating system, with comparable beneficial results. Senior management also regularly assesses the burndown curves from all projects to proactively recognize and handle possible problems [31]. Other benefits include promoting continuous improvement, reducing costs, increasing productivity, efficiency, and increasing transparency [34], [35].

This demonstrated that several key success factors for process development were effectively supported by incorporating principles from the agile methodology. These approaches are particularly relevant to this study as it suggests that an iterative stage should be included in the product development process. Although many opportunities arose in integrating these methods into waterfall methodologies, some difficulties in morphing these approaches were also identified, in **Table 3**.

Table 3. Challenges in the Integration of Agile Methodologies

Organizational Culture	
Decision-making	Both Developers and customers are involved in the decision-making process. This approach can be challenge. A culture built on trust must be fostered over an extended period of time
Documentation	Agile methodologies often lack documentation, which can be detrimental in scenarios where audit trails, regulatory compliance, or knowledge transfer are necessary
Resource management	
Predictability	The emphasis on flexibility and adaptability may result in decreased predictability in terms of project timelines, making it challenging for stakeholders or management to plan and allocate resources effectively
Standardization	The absence of stringent processes and standardization can lead to variants in team practices, making it difficult to establish consistent quality standards across projects and measure performance
Costumer involvement	
Commitment	Agile depends on collaboration, informed, and engaged costumers. Such participants can be difficult to find

Problems mostly arise from the shift of traditional values regarding sequential methodologies and the adaptation needed to successfully introduce agile techniques. These potential difficulties must be considered by businesses [5], [34], [35].

The table below summarizes the benefits and challenges in Agile, Waterfall and hybrid methodologies (**Table 4**).

Table 4. Benefits and challenges of Agile, Waterfall and Agile-Waterfall methodologies

Methodology	Benefits	Challenges
Agile	Flexibility and adaptability	Lack of predictability
	Customer satisfaction	Managing customer involvement
	Promotes collaboration	Lack of documentation
	Allows for iterative development	Challenging for large-scale projects
Waterfall	Clear project structure	Limited flexibility
	Well-defined milestones	Integrating customer perspective
	Easier to manage for small projects	Changes are difficult and costly
	Linear and straightforward process	Long development cycles
Agile-Waterfall	Iterative development	Integration issues
	Incorporates documentation	Balancing conflicting principles
	Flexibility while maintaining structure	Requires a skilled project manager

2.2.2 Multi-functional teams

Agile techniques are built on cross-functional teams and collaboration. Agile fosters close collaboration amongst team members with different skill sets, in contrast to traditional waterfall approaches where separate departments work alone.

As a result, the team makes decisions more quickly and effectively by sharing knowledge and encouraging a sense of ownership and collaborative accountability as show by the information flow represented in **Figure 11**.

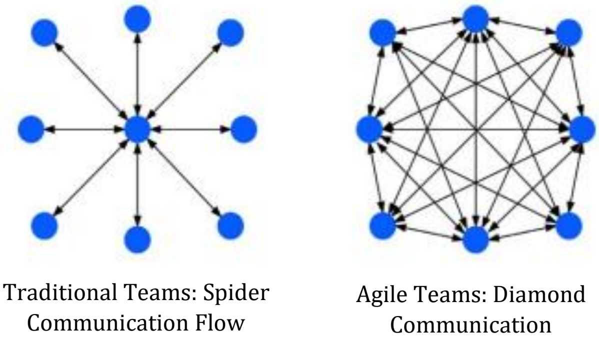

Figure 11. Traditional vs Agile team communication flow [31]

The difference in working structures allows agile techniques to be more flexible and to detect mistakes at an earlier stage. In the typical waterfall approach, however, errors tend to cost more when handled later in the process [31].

As the complexity of products grew so did the need to integrate multifunctional teams. The use of cross-functional teams has been widely implemented in new product development projects, leading to believe that higher relevance is given to multidisciplinary integration of different departments into product development tasks. Especially in business companies that function through a business-to-business model, where products are generally more complex, as shown in the example of composition of a product development cross-functional team for an industrial product (**Figure 12**) [28], [36].

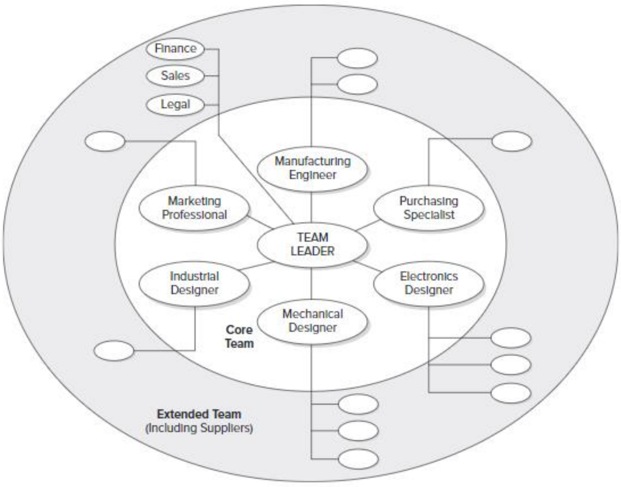

Figure 12. The composition of a product development team for an electromechanical product of modest complexity

Cross-functional teams are project groups that include personnel from multiple functional areas, such as engineering, manufacturing, or marketing. The fundamental logic is that the functional diversity of these teams expands the amount and variety of information accessible for product design. This enhanced information allows project team members to better understand the design process from a number of perspectives, which increases design process performance. Furthermore, the enhanced knowledge allows the team to detect downstream issues like as production challenges or market mismatches before they occur, when these issues are typically smaller and easier to resolve [2]. Thus, cross functional teams are associated with high-performing processes "Cross-functional units have been advocated as the most effective type of team to oversee development efforts " [28].

Edward McDonough observed a positive relation between the use of cross-functional teams and product development success factors. This is in line with the key factors reviewed in the success factor section, as flexible settings promote product development success. According to this study, managers more frequently decided to move to a cross-functional team set up to improve speed to market performance [36]. Also, from the sample derived, it was frequently mentioned as the 3 most important factors for cross-functional team performance, setting specific goals, strong team leader management and cooperation between members. This contrasts with other studies that point out, management involvement as the most important success factor for process performances, as task success may require more management involvement and resource allocation while team performance relies more heavily on the leader's management style [2], [28], [36].

Overseeing teams effectively can be extremely difficult, especially when there are different background areas separating team members. Distance theory studies attempted to establish a model to quantify a team's level of closeness. The research investigates the impact of distances in needs of communication and coordination, as well as ways to optimise these metrics [37], [38].

This theory can optimise the dynamics of multifunctional teams during product development and be used to identify gaps in communication. There are many forms of distances that influence team relationships and project outcomes. Physical, semantic, technological, and perceptual gaps have been found as important to product development teams. These are presented and explained on **Table 5** [37], [38].

Table 5. Crucial gaps for product development teams (Reproduced from [37], [38])

Aspect of Distance	Description	Improvement recommendations
Geographical Distance	Physical separation of team members	Use of virtual communication technologies and schedule regular meetings
Semantic Distance	Arises from diverse professional backgrounds and terminology	Clarify technical terms, encourage simplified communication
Technological Distance	Varied levels of technological familiarity	Provide training and ensure necessary tools
Perceptual Distance	Occurs as a result of different points of view and perspectives	Promote dialog and active listening

By overcoming these barriers, multifunctional teams can improve communication and promote rapid innovation, efficient problem-solving, cohesive teamwork to produce better results. Distance theories offer a framework for identifying and minimising the difficulties in managing multifunctional teams [37], [38].

This theory is especially relevant when considering customer integration as part of the product development method. Managing customer expectations and understanding customers are crucial to development success [37], [38].

2.2.3 Customer involvement methodologies

Customer interaction is regarded as a critical component in the success of product development, as discussed in the chapter on success factors. Agile methodologies and the current customer focused paradigm highlight the importance of involving customers in the process, crucial to achieve a successful product development [33], [39].However, an initial study, by Cooper et al. (1999), found little relation between customer involvement in product development process and product success.

This study analysed the impact of customer partnerships on new product development success rates and concluded that collaboration has a limited impact on new product profitability. It suggested that these limitations may be caused by the type of relation established, situations in which partnerships are created to target sales or marketing campaigns. Also, client involvement in partnerships does not address all flaws in the new product development process [40].

Customer alliances, according to the research paper, could improve certain drivers of innovative product success, such as acquiring a competitive advantage, aligning with existing resources, assuring high-quality new product development execution, and getting senior management engagement [40]. Even though these conclusions are true in the context of the study, new research points to a positive relation between success and customer involvement. Later on, Cooper (2019) pointed out that a deep understanding of customer requirements, the competitive landscape, and market dynamics is critical for new product success [39].

Kaulio (1998) reviewed different product development management models that include the customer's involvement. The study identified two dimensions of interaction, the depth and points of involvement [30]. The reviewed models suggested the user's intervention at different phases of the process as shown in **Figure 13**.

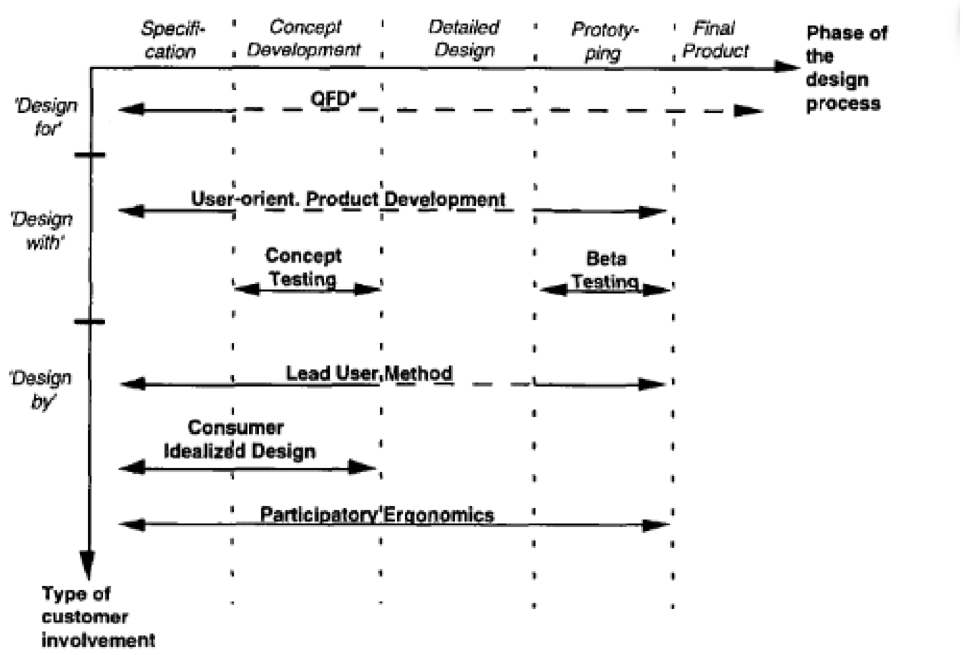

Figure 13. User's intervention at different phases of the process (reproduced from [39])

In the figure are denoted the specification phase, concept development, and prototyping as the phases where customer involvement is more commonly used [30]. Certain strategies for engaging customers are used along with agile methodologies, like design thinking, to understand their demands and interactions with products. These insights are useful during the specification process, as they contribute to the development of ideas [31]. Incorporating these methods during the most impactful phases for customer involvement can critically impact product development success [30], [33].

2.3 Industry 4.0.

Industry 4.0, also known as the Fourth Industrial Revolution, is a combination between developments in technologies and manufacturing processes. This represents a change in the industrial paradigm towards the technological integration of devices that enable smart connected systems and data collection. Industry 4.0 investigates the integration of cyber-physical systems, the IoT, artificial intelligence, and big data analytics to improve manufacturing productivity, efficiency, and flexibility. It has the potential to revolutionize multiple sectors and promote intelligent and sustainable industrial ecosystems. This surge of technological integration requires roadmapping tools for companies to guide the implementation of technological developments [41].

2.3.1. Internet of Things

Industries of the future are forecasted to become digitally integrated across all processes, often referred to as digital factories, smart factories, or information factories [41]. According to a survey conducted by Arcaini et al. (2015), 9 out of 10 companies have intentions to invest in digitalisation of industrial machinery [42].

This is primarily driven by market dynamics, the need to enhance customer proximity, achieve product personalization, and accelerate production timelines. Products have transformed into sophisticated devices, merging mechanical, electronic, and informational technologies, resulting in complex interfaces. These mechatronic products are seamlessly integrated into networks and communicate with one another. They generate, share, and utilise data to fulfil future functions, and are classified as IoT devices. **Figure 14** provides a general depiction of the components of an IoT device. An IoT device entails connecting hardware, software, internet/cloud platforms and end-user services/applications [42].

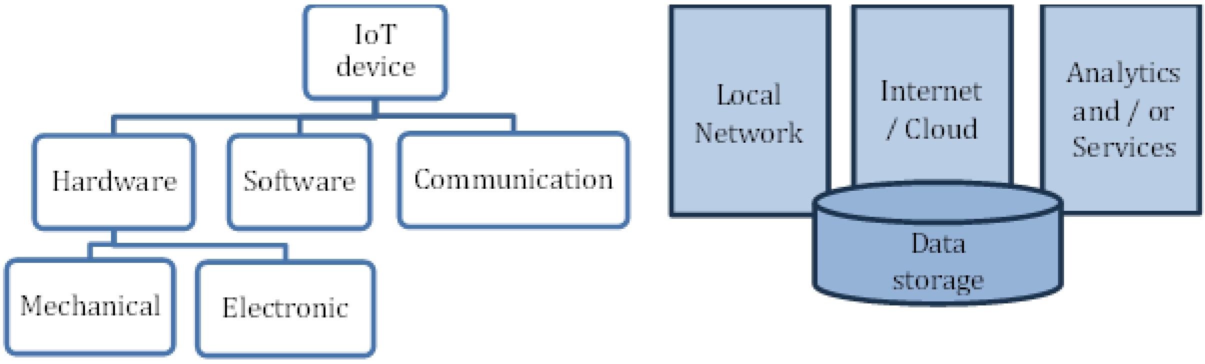

Figure 14. General elements of IoT devices (Reproduced from [43]).

A recent study on IoT integration within the product development process pointed out different advantages and challenges, based on a systematic review of literature. The advantages identified prevailed over the challenges, the more frequently referenced themes in the literature are aggregated in the table provided below (**Table 6**) [42].

Table 6. Benefits and Difficulties regarding IoT integration (Reproduced from [42])

Benefits	Difficulties
Reduction of costs in productive process and projects development	High cost of security and protection databases
Increase of quality in products and real-time processes monitoring	Lack of systems for internal integration and data sharing
Reduction in the time to develop products, projects and productive processes	High cost of implementation and adopting new technologies
Optimization and feasibility of process for the development of multiple products	Resistance to new technologies, cultural change

The benefits pointed out are resulting of the IoT's capacity of data gathering and producing data-based insights that better decision making. The enhancement of product quality and increase of efficiency is achieved through the increase in the comprehension of processes, products and their life cycles, facilitated by these technologies.

The fast flowing and real time information flow also leads to more efficient and integrated processes. Furthermore, IoT contributes to increase the flexibility of processes, allowing greater adaptability to change, due to technological advancements, and to more rapidly identify new market opportunities. The role of the customer in the product development phases is also facilitated by these technologies [42].

The problems identified are related to the costs associated with adopting new technologies, establishing the necessary infrastructure and organisational mindset. Implementing these technologies requires significant financial commitment and investment in effective cybersecurity and data protection. Internal systems and workflows are often inadequate to integrate change, which amplifies the magnitude of the investment.

Furthermore, organisations face challenges in accommodating workers to the adjustments for IoT integration, which results in greater technological distances between employees. Industrial companies with well-established processes experience even more difficulties as altering these types of procedures is often more challenging.

Data treatment and integration have been identified as major Industry 4.0 challenges that analytical methodologies such as Big Data can address, enhancing system efficiency [42].

Overall integrating IoT into products yields a positive impact on product development, nonetheless, companies must account for the challenges it presents [42].

2.3.2. Big Data

Today's technology has turned everyday users into constant producers of various data types, ranging from traditional unstructured data to structured transactional data [4], [44]–[47]. The product development and decision-making processes are being altered by the great amount of volume, constant generation, and variety of data.

Big data is characterised by the 3Vs (volume, velocity, and variety), it comes from a variety of systems and technologies, including social media platforms, sensor networks, online communities, and smartphone apps. It entails gathering and analysing user behaviour, performance metrics, and feedback [44].

It can contribute to the product development process primarily at three different stages: idea generation, design and testing. It adds substantial value to these phases as it enables a customer-centric approach and more informed decision making [4], [44].

Data gathered during the usage of a product can be integrated into the product development cycle as shown in the figure below (**Figure 15**).

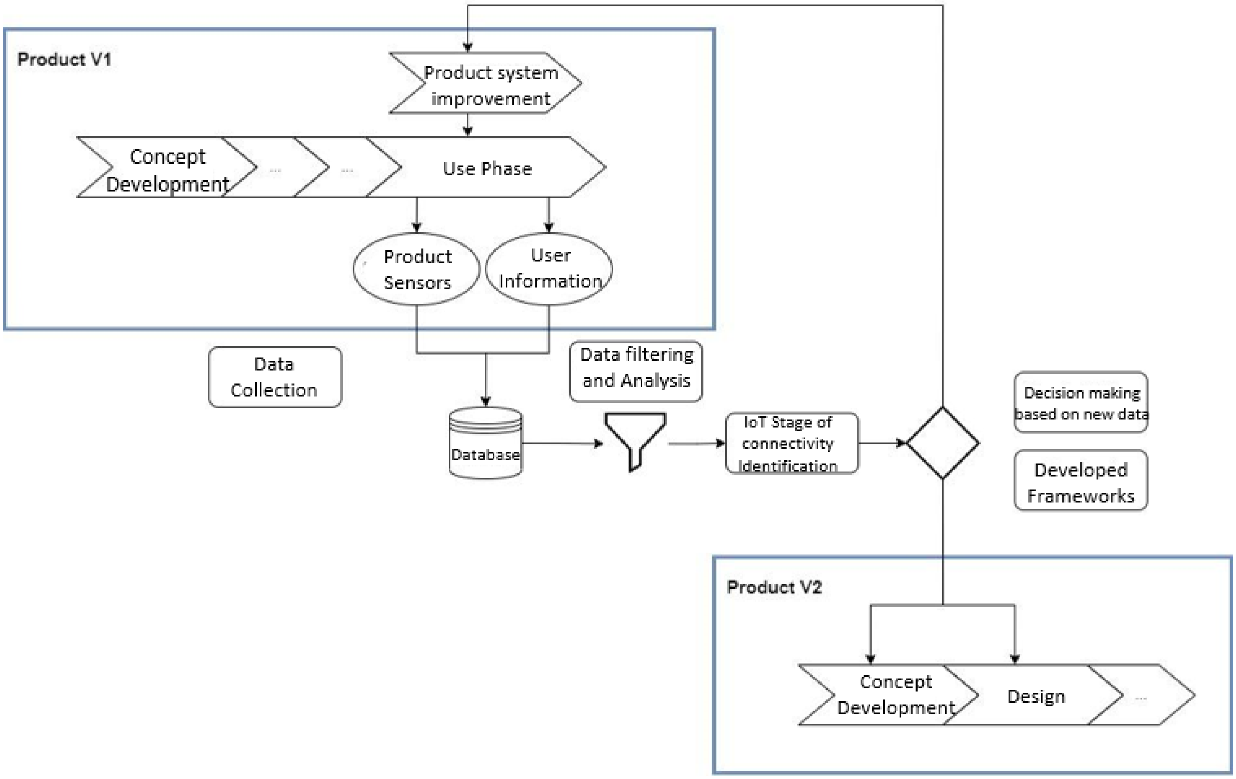

Figure 15. Product’s development cycle with integrated data from actual product usage (Reproduced from [50])

The integration online user-generated content (UGC) on product development activities generates positive effects. An empirical study highlighted the positive impact of UGC to the product development process in initiation and completion phases [44]. It enables products to serve users more effectively, to gain a competitive advantage, speed-up the product-development process and increase the product adoption [44], [47]. The study also points out a current trend in forming an ecosystem around a platform, where users can interact, enriching the quality and quantity of information available and raising product attractivity for customers [44].

Capitalizing on use phase data allows to gain valuable insights into how the products are being used, issues encountered by users and reveal areas for improvement. It gives a better understanding of the interaction’s users have with the product in real in practical situations, unveiling usage trends and helping decide which improvements to make. Furthermore, it assists in identifying usability problems that might not have been noticeable during testing or development phases. As a result, products become more reliable and user-focused. Additionally, data-driven insights can be used to iteratively improve products to increase customer loyalty and improve consumer satisfaction [4], [44], [47].

While use phase data yields favourable outcomes in product development, Wilberg et al. (2017) highlighted challenges within companies regarding the effective implementation of measures leading to the successful integration of such data into product development processes [45].

These challenges initiate during the planning phase prior to data analytics application. There are challenges in identifying methods for efficiently incorporating data into product development practices. Furthermore, a gap exists in current process models for data initiatives, offering limited assistance in systematically formulating a data strategy. Planning is essential to capture value from the collected information as many companies fail to align their data analytics with their business goals [45].

To diminish this gap in the literature Wilberg et. al (2018) developed a model to guide companies in developing a use phase data strategy and applied it to an industry case study, as seen in **Figure 16** [46].

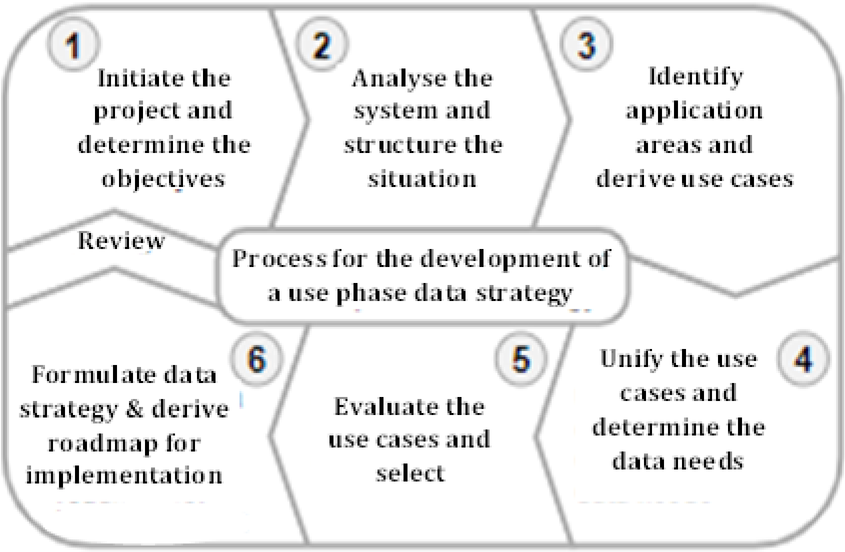

Figure 16. Process Model for the development of a use phase data strategy [46]

The six-step methodology supports the process of creating a use phase data strategy in a systematic way [46]. Although, it is very broad, and it doesn't specifically engage in the strategy itself or the application. The research in big data integration in the product development process has an emphasis on customer engagement and interaction. However, it is lacking research into feedback from industrial mechanical products.

2.3.3. Technology roadmap

Technology roadmapping is a strategic planning technique used by businesses to align technology development with their business goals and objectives. It offers a methodical approach to identifying, prioritising, and planning the implementation of technology initiatives [48].

This tool involves describing the organisation's current state of technology, analysing future trends and opportunities, and defining a strategic path to adopt and develop technology. It assists organisations in anticipating market needs and technological developments, it helps lower risks associated with technological investments and ensure efficient resource allocation [48]. Thus, roadmaps should be part of a continuous process in an organisation's life cycle to ensure its continuous technological development. In this sense, different roadmap applications have emerged across industries as they differ based on the industry and perspective they represent [49].

A framework developed by Phaal et. al (2003) focuses on managerial implications of technological improvements. The framework is structured into 3 pillars of organisations. Strategy, defining the future direction of the company. Innovation, the development of new products, services, processes, and supporting systems to sustain the business. Operations, the process of delivering products and services to market in an efficient way [48].

This broad model (ISAEP) divides into 5 processes the key activities a company can follow to develop a successful roadmap. **Figure 17** presents a schematic representation of this.

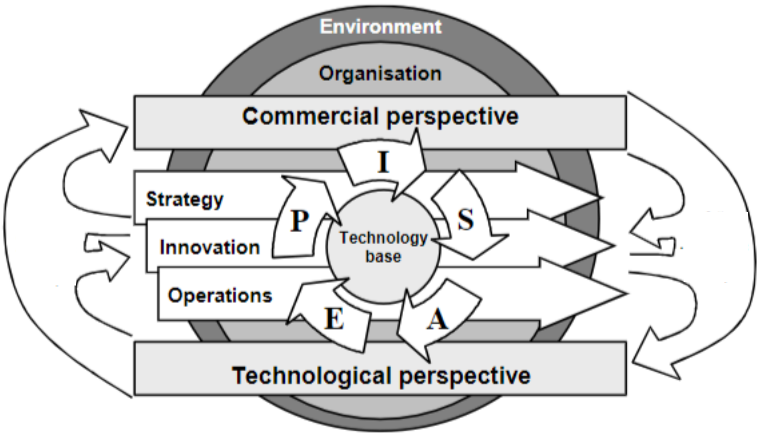

Figure 17. The necessary activities for a successful roadmap development (Reproduced from [48])

This 5 presented steps in the figure are described as follows.

I - Identify new technologies to the company that are relevant to present or future operations by searching for emerging technologies.

S - Select technologies necessary for the company's operations by establishing criteria and using decision support models.

A - Acquire these technologies to integrate into products or processes.

E - Exploit the technology to achieve business advantages by integrating it into products and services.

P - Protect the technology to minimise intellectual property loss. This involves creating knowledge ownership and documenting processes to prevent the loss of expertise

It is suggested that this model is customised to suit the specific case being analysed [48]–[50].

The application of these roadmaps can also bring some difficulties. Phaal et. al (2013) referred to some challenges found when applying this framework. The resulting model is only as good as the information and data is based on. The time and effort to input in the roadmapping project is considerable. Furthermore, the framework has to be customised to fit its particular context. This can be complex due to the lack of roadmapping expertise in industry which also represents a barrier to its adoption. Technology roamaps can be used by organisations to strategically plan their technology investments, effectively allocate resources, and align their technological and business strategies. This allows them to remain competitive, promote innovation and adapt to changing markets [50].

2.4 3D printing

3D printing is a manufacturing technology that has transformed different sectors, including product development. It entails building three-dimensional objects by layering materials based on digital designs. This technology has been gaining popularity as it produces complex prototypes with high quality and speed. It allows to materialize ideas into physical objects with a quick set up, ideal for the prototyping phase of product development [51]. Recently research on additive manufacturing has increased [52]. Initial 3D printing methods were costly and produced low quality products. Nevertheless, technological advancements in equipment, material and software contributed to reduce costs of the machines, increasing its access, and to improve the quality of the products manufactured [53]. With the lower prices, technology has become more accessible and production costs have also decreased. New technological advancements in 3D printing models have integrated IoT technologies, such as remote monitoring and cloud manufacturing [51], [53].

2.4.1 Impact on product development

The impact of additive manufacturing on product development is widely researched, as the use of these technologies in this field is increasing. It can primarily benefit the ideation, prototyping and launch phases of product development. 3D printers facilitate the communication and development of product ideas, by materializing them and creating physical objects from sketches and CAD models. Furthermore, this technology enables tests during development phases and promote iterative development methodologies which can contribute to the product's success. During the launch phase it can be used to produce product's prototypes and gather customer feedback before starting production. 3D printers can also be used to promote communication and user participation during design phases [54].

Literature highlights the positive effect of additive manufacturing technologies in the product development process. **Table 7** indicates the most frequently referenced benefits of the application of 3D printing technologies into the product development processes.

Table 7. Advantages of 3d printing in the product development process

Advantages of 3D Printing	Description
Rapid Prototyping	Quickly transform ideas into physical prototypes using digital designs, reducing development cycles
Design Flexibility	3D printing produces intricate designs, enabling the creation of complex objects and moving parts
Cost-effective Production	Ideal for low-volume or custom manufacturing, 3D printing eliminated the need for expensive tooling and molds
Functional Testing	Create functional prototypes for testing, evaluating product performance and making iterative improvements
Customization and Personalization	Tailor products to individual customer needs, catering to industries like healthcare, automotive, and consumer goods.

The benefits described contribute to accelerate the time-to-market of products by enabling quick prototyping options and rapidly transforming ideas into physical products. This also increases the flexibility of processes, as products designs are easily adaptable by these technologies.

For products with lower volumes, it provides a competitive alternative as set up costs are accessible. This technology enables the production of personalised products, relevant the current manufacturing paradigm of personalised production, and promotes iterative processes, due to the ease of implementing changes [51], [54], [55].

Literature suggests that IT and manufacturing departments should collaborate to enhance the benefits of using 3D printers. Furthermore, it is also highlighted that companies in markets with greater turbulence benefit more from using these technologies, as 3D printing technologies promote flexible processes and responses under uncertainty, companies can use this in their advantage [55].

Although incorporating this technology presents advantages, literature shows lack of approaches for its systematic implementation. There still seems to be “low adoption rates for a set of technologies that are three decades old and low success rates for digitised manufacturing technologies in general” [55].

Literature in the consumer perspective of 3D printer use is underrepresented. There is a significant knowledge gap enabling home users to fully operate 3D printers. Most users possess an engineering degree. Operating a 3D printer can also be challenging for a home user [56]. It's common for less experienced users to encounter challenges when using CAD design software, as it demands a specific technical expertise. This accentuates the existing gap in 3D printer accessibility [56]. Moreover, CAD software is extremely expensive, despite the fact that 3D printers can’t operate without them. However, this difficulties for unexperienced users is diminishing, as there are an increasing number of libraries and designs shared between users for free use. Sharing designs promotes collaboration and open innovation contributing to close this accessibility gap. Additionally, there is an increasing demand for knowledge to effectively operate and maintain 3D printers [56].

Literature presents multiple prospect developments for integrating new technologies into additive manufacturing. Although 3D printing primarily involves mechanical processes, it has great potential for the integration of IoT technologies [51], [53], [57]. Some of the IoT applications are remote monitoring, cloud manufacturing, automation, predictive maintenance, augmented reality, artificial intelligence and data analytics. These applications have positive benefits to additive manufacturing. A deeper analysis into remote monitoring and cloud manufacturing will be done since these are the most currently used and complete solutions of IoT technologies in printing machines, being aligned with the study's purpose.

2.4.2. Remote monitoring

Ma et.al (2015) developed a study aimed to integrate IoT technologies into 3D printing. The research analysed possible sources of data gathering through sensors, cameras and developed a platform to monitor the printing process [57] The structure of the data collection is represented in **Figure 18**.

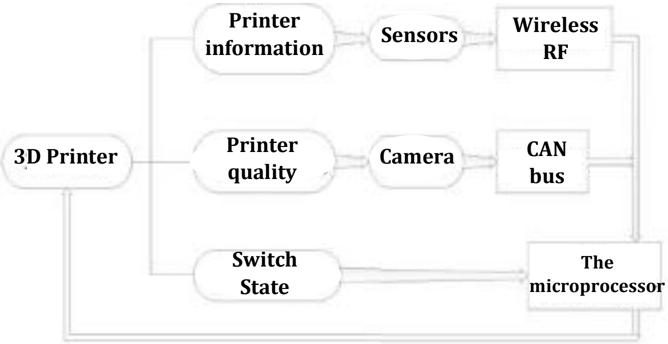

Figure 18. Structure of data collection

IoT integration provides advantages to 3D printing. Devices enable remote controlling, allowing users to start, pause or stop printing jobs, which increases flexibility and convenience [57].

Sensors can monitor different types of data, such as temperature, printer head movement and material shortage, during the printing process and transmit this data in real time. This increases the user control over the process [57]. Real time monitoring allows users to have an overview of the process status and printing conditions from afar. Progress updates and error detection ensures a better printing experience and helps preventing printing failures and consequently material waste [57], [58]. Integrating cameras provides additional monitoring capabilities, which paired with artificial intelligence allows to effectively detect printing errors [58].

Although these remote monitoring functions provide increased control, over the process, to the user, it still requires the manual intervention for many operations. Some printing technologies were developed in this sense, such as autonomous removal of finished pieces to allow another print to start without manual intervention. The integration of IoT technologies in 3D printing, as well as data collection applications and sensors, enhances the printing process increasing efficiency, control, and knowledge, allowing users to stay informed about the status of their printing projects [57], [58].

2.4.3. Cloud Manufacturing

Cloud manufacturing incorporates cloud technologies into the printing process, enabling web-based data storage and control options. Cloud solutions improve user experience as it provides data management features and connection to web instruments. This allows users to share designs and explore libraries online, a relevant improvement especially for less experienced users. It fosters the creation of a community and promotes collaboration between users, which benefits and attracts costumers. Building a community around a product and offering platforms so that users can interact with each other increases customer satisfaction. Furthermore, this allows users to engage in product design through these platforms [52], [59].

Cloud manufacturing also investigates the possibility of resource pooling, allowing inactive printers to be remotely used by other users. These interactions are possible due to remote monitoring and cloud platforms. Users can 3D print objects, from designs gathered on an online library, without the need to own a printer. One of the most referenced structures for cloud a manufacturing system is represented in **Figure 19**.

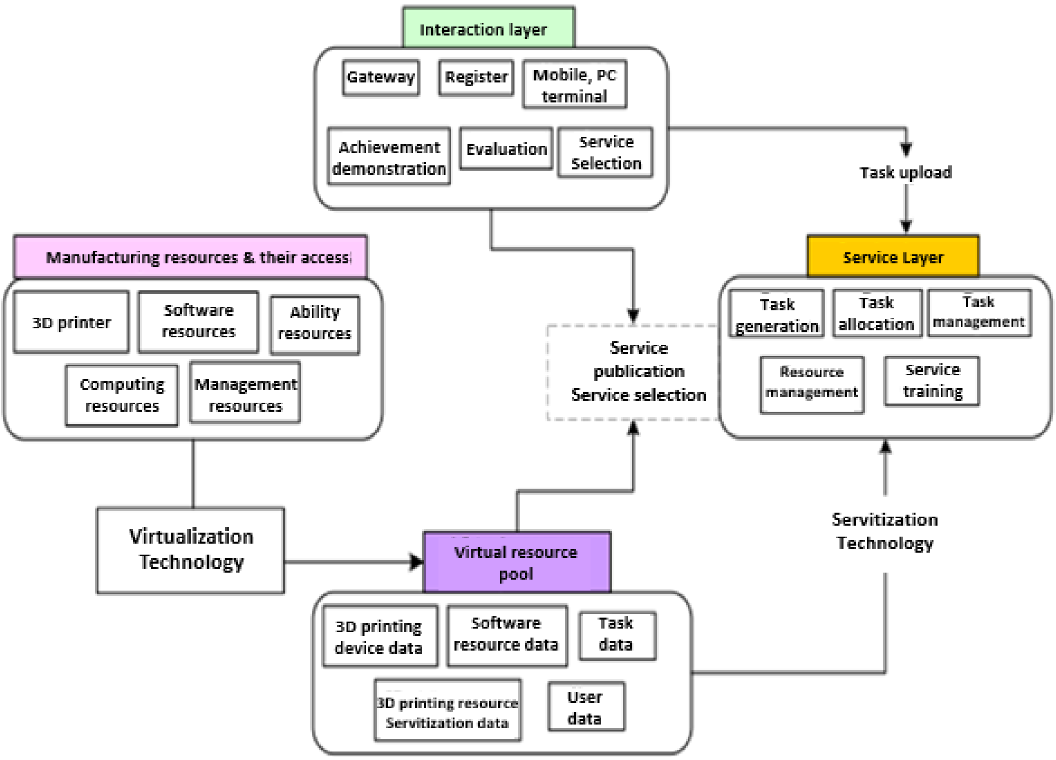

Figure 19. 3D-PCP framework in recent studies (Reproduced from [52], [59])

The presented structure is composed of four layers. Manufacturing resources are physical printers, digital designs and software available in the cloud platform. The virtual resource pool contains the status of the resources available, with virtualization technology, and gathers digital data. Service layer manages the resources in use and operates as the task manager of the system. The interaction layer offers the user the interface to make use of this system. This technology is set to be used in manufacturing ecosystems where sharing resources is possible for a more effective use of 3D printers, improving user experience and the possibilities offered [52], [59].

3. Methodology

The methodology used entails an analysis of the 3D printing case study within different areas, technology, user perspective and organisational changes. This allows for a deeper understanding on how IoT technology influences on products and product development processes. From this analysis, a framework with wider industrial relevance is generalized. The methodology follows the diagram presented **Figure 20**.

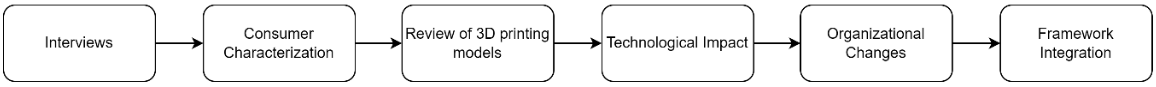

Figure 20. Diagram of the followed methodology

This structure to the methodology resulted naturally from the analysis of the literature review, as these different steps are crucial pillars to the development of a comprehensive framework towards integrating technology. The analysis starts with a qualitative research, interview-based questions, to understand how users perceive 3D printing technologies and how it has affected their work. Including insights from users into the analysis aligns with a customer-centric approach. This is followed by the identification of 3D printer’s consumer groups that contributes to the characterization of distinct consumer segments. The analysis on 3D printing models help to further understanding the features and technologies offered by printing machines, and discover the benefits gathered from technological integration and its requirements. The organisational changes are analysed relating the technological advancements with the required expertise and functional structuring of teams. The integration of these different aspects results in a comprehensive framework that describes the requirements at each level of connectivity as well as the benefits expected.

This methodology allows to identify the expected benefits at each connectivity level, the organisational modifications and the connectivity features that are required to improve product’s connectivity, although it is important to recognise some limitations. The scope of the framework is restrained to the referenced areas. Important aspects such as the resource allocation of time and investment are not fully addressed. Moreover, the framework is derived from a specific case study, confining its reach, especially in terms of technological advancements, to the example analysed. This potentially limits its applicability to other industries.

The choice of the case study subject aligns with the objective of the study. 3D printing machines offer a wide range of connectivity features to monitor its process, generate data and support software, making it ideal to study what is proposed. A case study attempts to transfer specific findings from one unit or group to multiple units. It is less applicable than a general example, but it formulates more pertinent managerial recommendations and empirical findings. Although, a case that is extensively similar across product development processes is harder to find and analyse.

Furthermore, 3D printers are frequently cited as the future of manufacturing and are used in multiple industries [52], [56]. It is expected for the 3D printing market to grow at a 18-27% rate the next few years

[60]. The increase in popularity of this production method makes it an appealing case study topic, as its relevance to the manufacturing industry and research in this field grows. Beyond this, 3D printers produce final products aligning them more closely to the manufacturing industry.

The wide range of printer's characteristics allows to visualise the evolution of printer models, making it possible to observe and study the incremental added value by the technological features. Lower-end models can still produce a 3D printed product, however more advanced models offer more features. Moreover, 3D printers are getting increasingly more connected to external devices, to remotely control and monitor the process, via sensors, wireless connection and software integration.

4. Results and Discussion

4.1 Interviews

Initially, informal interviews were conducted to create a better understanding of 3D printing technologies and to gather data that contributed to the research developed. Moreover, introducing user insights contributes to make the analysis in line with the consumer perspective.

These interviews kept informal to encourage a free-flowing conversation rather than performing a questionnaire type format. To gather better insights and personal experiences from the participants, it was used open-ended questions that promoted flowing dialog, which proved efficient in gathering the necessary information.

The participants were selected from university students and alumni that currently interact or have used 3D printers., and to include different perspectives, the participants had different printing experiences and engineering backgrounds. Some guideline questions were used to lead the conversations and guarantee that relevant topics were covered. The interview questions are spread between four main topics, as shown in the table below (**Table 8**).

Table 8. Interview questions and categories

Category	Interview Questions
User background	What is your experience with 3D printing technologies?
	What types of 3D printers have you used?
	In what contexts have you used 3D printing
Technology awareness	What type of features or capabilities you value on a printer?
	What do you think of the state of 3D printing technology?
	What advantages and disadvantages do these technologies bring?
Impact evaluation	How has 3D printing affected your work or projects?
	What type of challenges have you encountered?
Future expectations	What do you think the future of 3D printing technology is?
	What type of advancements or improvements do you foresee?

Three different participants contributed to these interviews. The limited sample of participants is a limitation to the analysis, although the participants chosen have extensive knowledge in the area which proved more fruitful, in contrast to reaching a wider sample less experienced in the area. The first participant experienced working with 3D printers to produce a prototype during the master thesis in materials engineering. The insights given concentrated on different printing materials and material handling has the research was focused on investigating materials conditions. The participant referenced the importance of precision, quality of printing and the ability to work with different materials. The rapid prototyping feature was crucial to the work developed, guaranteeing the quick production of a usable prototype. Although, it was denoted some difficulties in operating 3D printing technologies and the post processing process was described as time consuming. The participant expects 3D printing to be widely used and to have better and more sustainable materials.

The second interview emphasised precision and control systems as the participant had a deeper understanding of developments in the field and worked more closely with different types of printers. The participant, a mechanical engineer in the field of product development, modifies and develops new 3D printers to better suit research requirements. It was emphasized the value of precision and versatility the machines offer, that resulted in more efficient production and promotes research. Challenges in balancing the customization of printers and cost were denoted, as well as keeping up with the rapid technological advancements. It is expected improvements in the user-friendliness of interfaces and greater flexibility in machine setups.

The third participant was an entrepreneur, with a background in electrical engineering, engaged in research towards new 3D printing mechanisms, demonstrating extensive knowledge regarding mechanical features and software integration. In the interview was pointed out the value in the 3D printers adaptability to meet specific manufacturing needs, increase processes speed and efficiency. Remote monitoring features were denoted to bring flexibility and convenience to the process although room for improvement was referenced, especially, in minimising the requirement of manual intervention. Difficulties in developing firmware and automation was identified. Advancements in automation with the integration of data collected and AI into the machine software in a feedback loop is expected.

The conclusions from the gathered information revealed:

- Versatility Matters: The interviewees emphasised the importance of having diverse machine features for different project demands. Having versatile printer options allows to create a more customised and adapted production process to the specific needs of the project. Some require higher precision whilst for some developments speed or connectivity can be more valued.
- Precision is key: Technology developments and the increase in materials quality have highly improved precision. The requirement for high precision was referred by every participant. Although different projects require differing levels of accuracy, it is crucial to consider the trade-offs between quality and other features when choosing printers.
- Technological Advancements: Participants revealed to have different knowledge regarding existing technologies, focusing on their own research areas. It was recognised advancements in user interfaces, automation, and control systems. In addition, they expect developments in flexibility, speed, user friendliness and sustainable printing materials. Furthermore, it is expected the reduction of manual intervention enhancing automation and remote controlling options.
- Challenges Exist: User friendliness is a challenge, especially for less experienced users during the product design process. Even more, integrating the collected data into the printing software to allow for real automation and feedback loop into the machine is complex and underdeveloped.
- Impact on Product Development: The introduction of 3D printers in their work allowed for rapid prototyping, which revealed to have the most positive impact to quickly developing products for

a more effective study. Also, the machine’s flexibility increases the speed and efficiency of processes.

- Future Outlook: For the future of 3D printing technologies, participants expect an increase in precision, improvements in automation and efficiency through AI, and user-friendly interfaces. Also, a wider adoption of these technologies with improved flexibility, materials and predictive maintenance features

The participants' varied backgrounds and user experiences offered a wider perspective that improved the conclusions drawn. One important finding from these interviews is that post-processing procedures and manufacturing costs can be reduced with the use of technological developments and efficient integration. Technology advancements and integration can help to smooth manufacturing process and save associated costs by improving efficiency in 3D printing. Moreover, creating a better understanding of the process, can help solve the problem of user-friendliness, which frequently came up in the interviews. Manufacturers can better understand consumer behaviour and preferences with the gained insights from gathering and analysing data generated during use phase. By utilising this knowledge businesses can create 3D printing solutions that are simpler and easier to use. Some of the different 3D printing models referred during the interviews will be further analysed in the printer’s characterisation chapter.

4.2 Consumer groups characterisation

To initially identify 3D printer models on the spectrum of connectivity, it was observed through different 3D printers that IoT features have generally a stronger presence in higher priced models, whilst lower priced models operate offline and offer basic functions, which translates into a positive correlation between price and incorporated features. Another remark is that different models are specially produced considering a specific type of customer and what features the customer values considering the end use for the machine. This leads to a wider variety of printers where even in the same price range some can include different features that target different customers.

To characterize the different 3D printers, it was examined the purpose for which customers buy a printer. This also favours a customer-oriented approach into developing this framework.

According to various websites and the reviewed literature, there are different type of customers which give different use to the printers, have various buying purposes, and different levels of expertise [56], [60], [61].

- Home users: Enthusiasts and hobbyists use 3D printers for personal projects, crafts, and DIY. These consumers have little expertise in the area and buy this technology for personal enjoyment.
- Educational Institutions: Educational institutions use 3D printers to teach students and allow interaction with this technology. 3D printing is used to promote research in the product

development field and prototyping for various projects. The user knowledge for this group of users can vary from new to the technology to experts.

- Entrepreneurs and Small Businesses: 3D printers are used by small businesses and entrepreneurs in startups to efficiently produce prototypes and products for low volume demand at a lower cost. Additionally, it is used to manufacture customed and unique products. The users usually have experience with this technology.
- Professionals: This group of costumers use 3D printers to quickly test their designs with rapid prototyping. Professionals have extensive knowledge on the technology.
- Industrial manufacturing: Manufacturers utilize 3D printing in the large-scale production of customised products. This technology is used in the aerospace, healthcare, and automobile industries. This group of customers are experts in operating these machines.

Different models are targeted at these customer groups which have varying printer feature preferences.

Let's firstly investigate what do consumers generally look for when buying a printer and characterise the previously identified customer groups by the features they value on a printer. From the interviews, literature and reviewing websites charactering 3D printers, some features appeared as the most relevant to customers: quality, cost, building volume, printing speed and noise, connectivity options and the ease of use. There are also more technical options that influence the decision of a printer, for instance, the bed levelling, dual or single extrusion, the type of materials it supports and the type of printing technique. Although they are not relevant to this study and will not be analysed.

As referred in literature, the cost of 3D printers has decreased and printers have become more budget-friendly, increasing its accessibility to more customers [56]. Affordability is one of the top factors for home users. Cost is prioritised over quality, by home users, as their primary goal is personal enjoyment. As they are less experienced, ease of use is valued as well as a supportive user community and a smoother interface. Furthermore, these customers favour printers with easy set-ups and compact designs.

Educational institutions value user-friendliness so that students can operate machines without in depth knowledge. It is preferred printers that support educational software, safety features, certifications for classroom use and are reliable, so that it requires minimal maintenance.

Entrepreneurs choose cost-effective printers that balance quality and price for small-scale production. They also prefer a user-friendly interface for a quick set-up and operation, along with some connectivity options.

Professional users prioritise quality over connectivity options, although they value remote access features. Printers should have flexible material options, consistent performance, and high precision which is crucial to produce reliable prototypes and higher quality products.

Industrial printers operate at the highest quality standards, speed and efficiency. They offer large building volumes, for large-scale production and compatibility with high quality materials. These machines are highly customised to the users' specifications and the requirements of production and offer automation and data collection features that are crucial to optimise production efficiency.

The information regarding the described customer groups is presented in **Table 9**.

Table 9. Customer group characterization

Costumer Group	Intended use	Characteristics valued
Home users	Personal objects	Low-cost; ease of use; connectivity
Educational Institutions	Education and research	Ease of use; educational compatibility; reliability
Entrepreneurs	Prototyping and low-volume manufacturing	Cost-effective; printing speed; ease of use
Professionals	Prototyping and designing	Quality; flexibility; printing speed
Industrial manufacturing	Large scale-production of customised products	Quality; automation; printing speed

Each customer group favours distinct features, according to the end use for the printer, which guide their printer selection. By gathering these characteristics, it becomes clear which printer models appeal to each customer group as many models are targeted at these distinct costumer categories.

4.3 3D printer's characterisation

Following the characterisation of the 3D printers market customer segment, various models are reviewed. Models present a wide range of characteristics, some prioritise precision and quality with some connectivity features whilst others offer lower quality at a reduced price point. Certain models favour higher quality over connectivity, and some offer instead more material flexibility. This makes more difficult to group these different printer models.

By analysing different models, the common characteristic observed for every printer is the price. Furthermore, there is a positive correlation between price and quality.

The more costly the model the more reliable, durable, and efficient it is, producing higher quality products, on the other hand, lower priced models produce lower quality products with less reliable results.

3D printers' models can be gathered into 3 distinct groups: budget, professional and industrial printers. When looking into different printer brands, most of them follow this rule, having a lower priced model with lower quality, an intermediate one that offers some other options, and a higher cost one with top-notch features.

The models analysed to characterise 3D printers, are represented in **Table 10**.

Table 10. 3D printer models reviewed

3D printer models	
Creality	K1Max AI Fast
	Ender-5 S1
	Ender-2 Pro
Monoprice	Monoprice Joule DIY
Anycubic	Anycubic Kobra 2 Pro
	Anycubic Photon M3
Dremel	DigiLab 3D45
	3D40-FLX
Markerbot	Method Platform
	Sketch Platform
Prusa	Original Prusa MK4
	Original Prusa MINI
	Original Pruse i3 MK3S
Ankermake	Ankermake M5C
	Ankermake M5
Markforged	Mark Two
	X7
	Metal X^{TM} System
Formlabs	Form 3+
	Fuse 1+ 30W
Ultimaker	UltiMarker S7
	UltiMaker Method XL

The models were chosen after gathering information on popular 3D printing brands from online sources and obtaining input from the interviews.

Budget printers range from 150€ to 500€ and are aimed at enthusiasts and home users. Creality offers different options according to the type of materials and technology. It has lower end models that sell for only 130€ that can be easily set up and print objects with a simpler interface. It also offers printers with high speed printing and a more accurate bed levelling. They also have a flagship series model for higher quality and industrial applications that could enter the professional printers group. It includes sensors, an AI powered camera for error detection and some automated features. Monoprice sells cheap printers with enough features to do the job. It is ideal for beginners who just want to have contact with 3D printing technology without a substantial investment. Anycubic employs a similar strategy, it has a big printing community and offers some quantity discounts, which could be interesting for institutions.

Professional printers go from 500€ to 2.000€, aimed at professionals, institutions, and entrepreneurs. Dremel printers offer easy to use features, are reliable and quiet ideal for everyday usage targeting students and class environments. These models also offer user-friendly software with cloud connectivity and remote controlling, that allows to queue prints, run reports and analytics, or even share access with remote users. MakerBot offers multiple connectivity features focussing on targeting professionals, small businesses and researchers, and emphasising quality, reliability and multiple materials compatibility. Prusa has a big printing community and support resources to ensure a seamless experience. It offers high quality prints aimed at home users who are willing to invest more in their 3D printing experience.

Ankermake is a more budget-friendly option in a lower segment of this group, specialising in high-speed 3D printing machines.

High-end printers are designed for industrial and high-quality manufacturing. Frequently, these printers are custom-made to meet specific specifications and requirements. Markforged offers a wider range of printing materials, high quality and precision, along with integrated software to ensure some production automation. Formlabs has desktop printer designs with high quality, speed and a strong customer support. Their website offers a wide-ranging look at their whole catalogue, along with detailed printer specifications and the option to compare different models.

Ultimaker printers have high quality prints and integrated software management capabilities. The different models analysed can be classified into the different groups shown in the **Figure 21**:

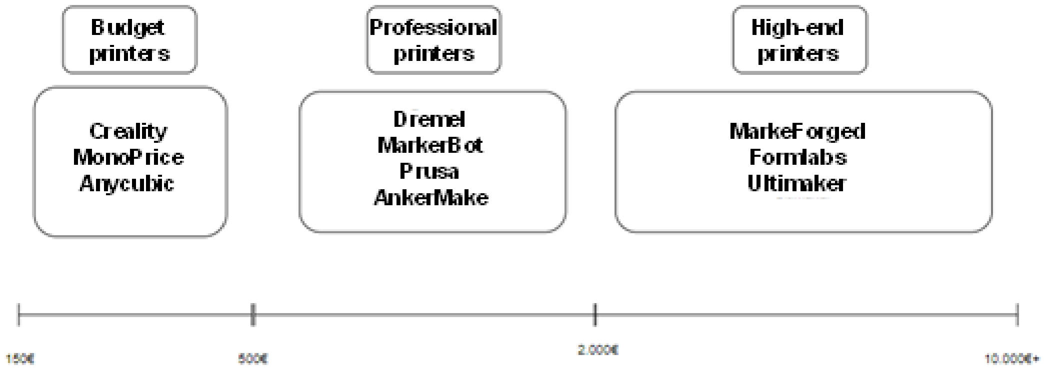

Figure 21. Categorization and Pricing of 3D Printer Models

The review of this models revealed that as the printer quality increases and the closer it is to high-end models, the less emphasis is placed on connectivity options. High-end printers give priority to increased quality prints for industrial applications, precision, reliability, flexibility, and automation while still offering connectivity features. For these machines it is crucial to have the highest quality standards.

Connectivity reveals to be more important for professionals' printers, where there is a greater range of features that sets models apart. As higher speed and quality come with a higher price point there is a cost-effectiveness trade-off for these options. Customers base their decisions on a balance between cost and these characteristics or considering the integration of connectivity alternatives.

Figure 22 describes these groups based on the various printer features.

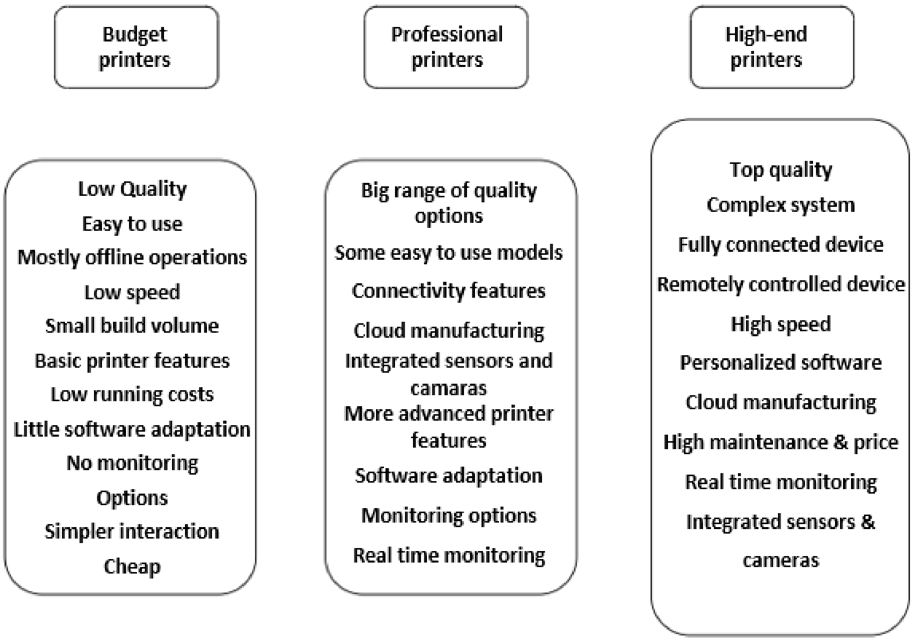

Figure 22. 3D printers' characteristics

The professional printers' category can be subdivided into different groups according to their levels of connectivity due to the multiple characteristics and connective features these models have.

4.4 Connectivity options analysis

Literature highlighted multiple connectivity features and technological applications for 3D printers, raging between simple models to fully connected devices. Typically, the simplest models start with integrating simple technologies. Sensors are the most common technological element in lower priced models. These devices monitor basic printer activities like filament status, extruder tension, extruder temperature, nozzle force, and so on. The figure in the **Appendix** (Appendix A)**,** illustrates different types of sensors and their position in the printers. Temperature sensors measure the printer's heated bed and the extruder nozzle. They ensure that the correct temperature for the printing material in use is maintained, preventing difficulties in the printing process such as warping and nozzle blockage. This is crucial to ensure consistency throughout the printing process and guarantee a constant flow of the material.

Extruder tension measures the strength of the extruder gear grip on the filament. High stress causes damage to the filament, reducing print quality, while low force can lead to clogs or under extrusion. Load cells detect extruder tension and regulate it in real time to ensure smooth printing. Sensors that measure nozzle force can be used to evaluate the printing speed.

Bed levelling sensors ensure that the building platform is levelled. These sensors contribute to successfully apply the first layers and maintain this consistency throughout the printing process by doing automatic adjustments. This is one of the first increments that can be applied to lower end models to improve printing quality.

End-stop switches are used to calculate the printer's home location and limits of movement along each axis. They calibrate the printer's starting point and prevent it from going beyond its physical bounds. The precision of these sensors is crucial to increase printing quality.

Filament sensors detect the presence of filaments in the printer’s extruder. When filament runs out, the sensor can cause the print process to stop, allowing the user to change the filament and resume printing. It contributes to diminish print failures caused by lack of filament. It also lowers the need for user intervention as the sensor can automatically interrupt the print as it detects lack of filament.

Cameras are usually the last technological element added, although their application is growing in 3D printers. It is used to record the printing process and identify printing errors with picture recognition and AI integration. These cameras provide extended features for remote monitoring and cloud manufacturing technologies. Combined with software and AI it is possible to detect precise errors and define thresholds for the product’s quality. Companies, such as AI build, are investing in integrating AI in the printing process, via these IoT devices. The different sensors and their measurements are presented in **Table 11.**

Table 11. Sensor Types and Their Measurements

Sensor	Measures	KPIs
Temperature sensors	Extruder and bed temperature	Printing quality
Extruder tension sensors	Nozzle tension	
Bed levelling	Bed levelling	
End-stop switch	Nozzle location	
Nozzle force application	Nozzle force application	Printing speed
Filament Run out	Material shortage	Process interrupt
Cameras	Error detection	Error percentage

These measurements can then be used to develop Key Performance Indicators (KPIs) and assess the condition of the printing process [57].

As illustrated in **Figure 23** these many data sources generate raw data, which serves as valuable input for the development of analytics and in-depth insights. By collecting and analysing this data it is possible to create advanced analytics that enable organisations to get a deeper insight of their processes, machine performance and consumer behaviours. This contributes to better decision-making, promote innovation, improve control and efficiency of the processes.

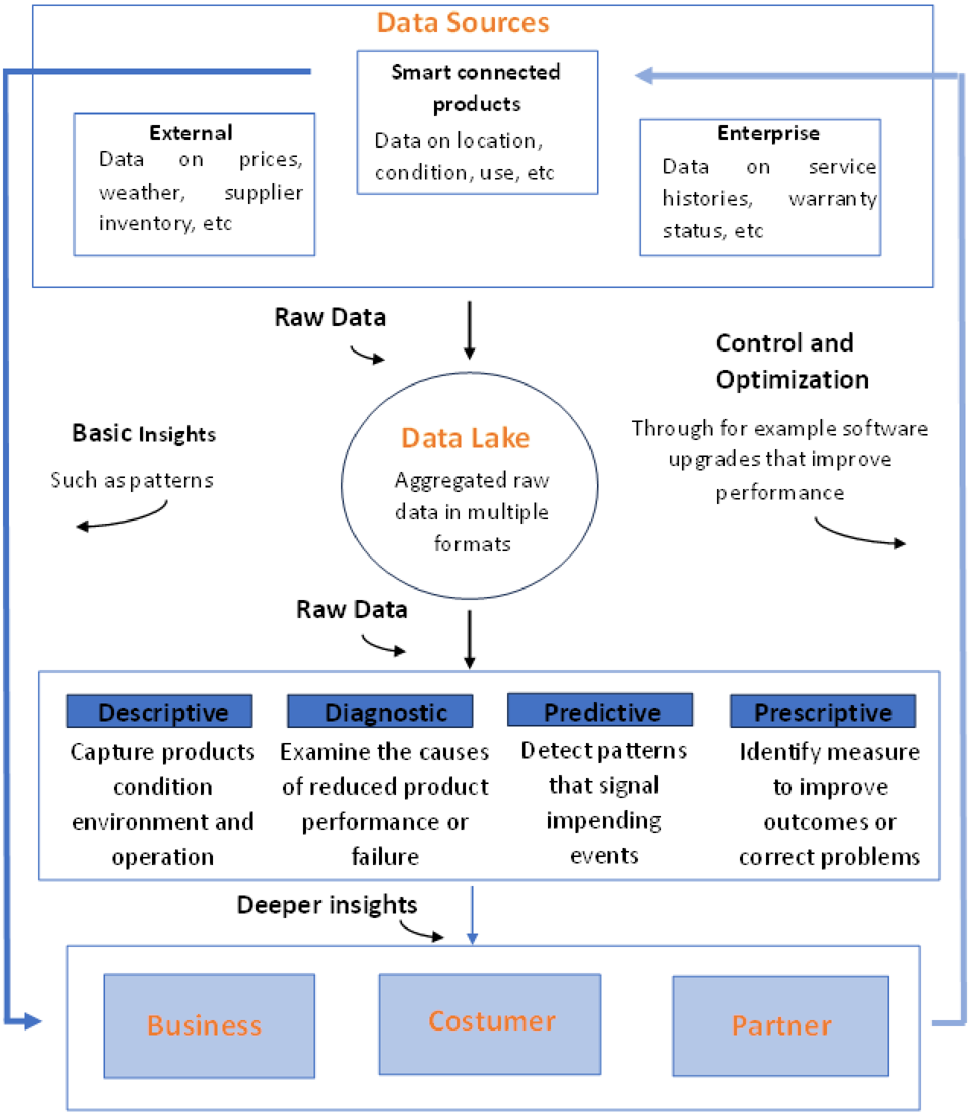

Figure 23. Data flow in IoT products (reproduced from [62])

In the context of 3D printing, descriptive analytics characterize the current state of the machine and the printing process, with a focus on quality and status measures. Diagnostic analytics are collected from camera-based error detection and the setting of thresholds for measurements to identify faults. Predictive analytics in 3D printing use operational data to assess the machine's state and enable operations such as predictive maintenance. Finally, prescriptive analytics suggests plans of actions that are triggered when thresholds are exceeded, ensuring suitable reactions to changes in the machine’s status.

This data flow model is similarly applied to 3D printers. The schematic representation of this information flow in a 3D printing process is presented in **Figure 24**.

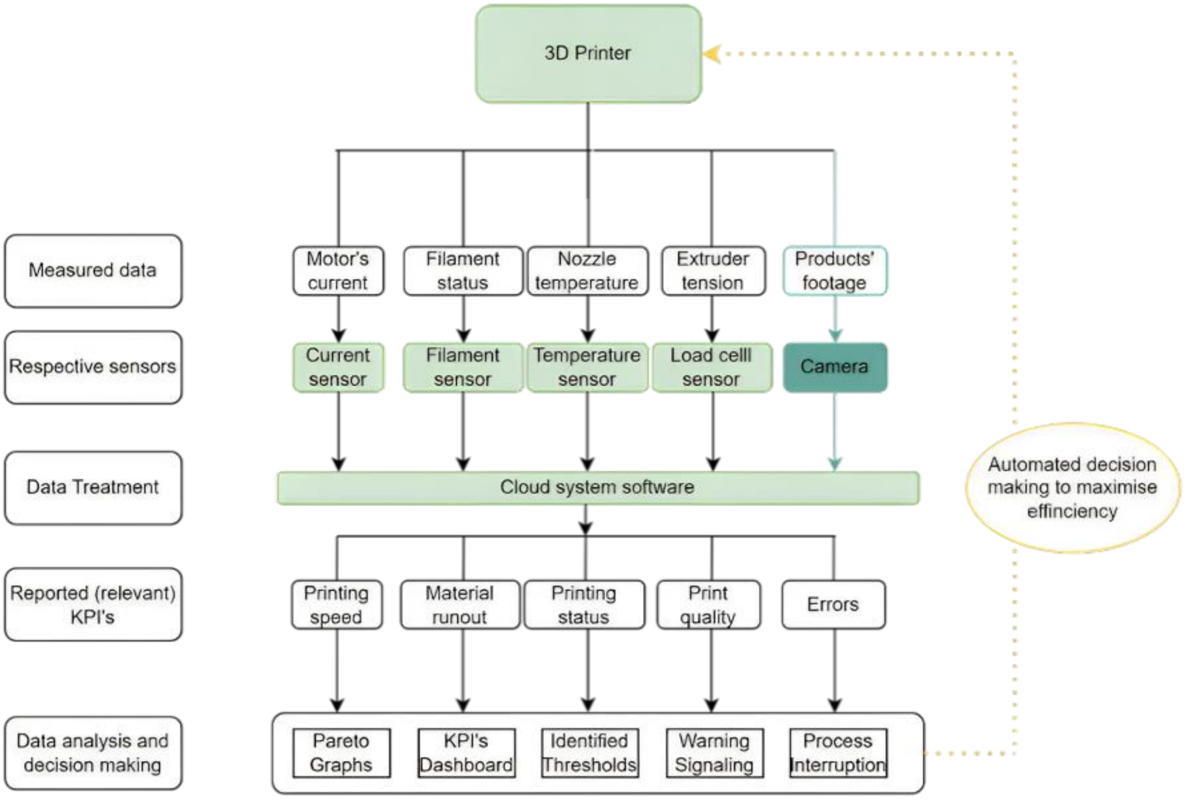

Figure 24. Schematic Illustration of Data Gathering with 3D Printing Sensors

The representation depicts the flow of information from some generic printer sensors, which measure the specified parameters. This data is processed by software and cloud technologies, resulting in the generation KPIs, which are then shown on dashboards, allowing to assess the status of the printing process, and set up potential warnings for a smoother process and data management. This data can then be used for decision making and an active management of the printing process.

Setting quality measurement thresholds helps to improve quality by identifying acceptable error levels or deviations from quality standards and implementing warnings when these thresholds are exceeded.

It is possible to predict the remaining print time in real time with the data generated from printing speed KPIs as well as detect material flaws that affect this measurement. Setting thresholds for error detection allows to detect major errors that require manual intervention or to stop the printing process.

Dashboards help to streamline data and present easy to interpret information that grants greater control over the process. This requires the use of software and data management tools that can be accessible online, while for more adapted options, in-house developed software increases complexity and connectivity of the product.

High-end printers incorporate complex software that integrates this data into the printing process and autonomously adapt mechanical functions according to the data gathered. This automation process requires extremely complex firmware development, achieved by improving the software that controls the machine movement and integrating the data gathered into automated decision making, ultimately resulting in increases on the overall quality of products and efficiency of the process.

The advantages of incorporating sensor and different technologies into the printing process are illustrated **Table 12**.

Table 12. Technology integration and benefits

Measurements and technologies	Benefits
Print quality	Increased precision, reliability and process knowledge
Printing speed	Greater efficiency
Process interrupt	Prevent print failures
Remote monitoring	Enhanced convenience and efficiency
Data analytics	Enables better managerial decisions; saves time & resources
Error detection cameras	Higher printing success rates; material waste reduction
Could manufacturing	Supports collaboration, outsourcing and increased flexibility

Sensors that measure print quality ensure that the products meet the standards defined and allow to detect real time deviations, creating an increased control over the process. These sensors are essential for applications where precision and reliable production is crucial.

Speed sensors help to estimate the remaining time to complete the print and identify issues like slowdowns or accelerations, which contributes to a more efficient process. Detecting process interruptions helps to prevent printing failures and alert the user when requiring manual interventions.

Gathering the information from these sensors allows to monitor the general printing status and integrate monitoring technologies. This facilitates managing printers as the printing status can be checked from afar, enhancing convenience and efficiency as multiple printers can be simultaneously managed.

Data analytics software enables the creation of dashboards and structures data that is used to make supported managerial decision. This technology provides a thorough look into the printing process and can be used to detect trends and patterns that promote process optimisation and helps save resources.

Error detection sensors and cameras contribute to increase print success rates as it helps to detect issues during the process and early flaws to prevent the waste of time and materials.

Cloud manufacturing allows to remotely control and manage printers through cloud platforms. This promotes collaboration, outsourcing printing tasks and offers greater flexibility.

From lower to higher end models, these technological features are usually integrated in a specific order. First, there is the need to gain control over the process and enhance data collection to improve quality. Then, the implementation of printing speed sensors and process interruption measures to allow remote monitoring options. Next, the introduction of remote control and data analytics capabilities to enhance flexibility and knowledge. Finally, enable cloud manufacturing for complete remote access and control, and implement software to manage these functions with precision and efficiency.

These implementation steps align with the identified models and their corresponding price points. This can be represented in the following scheme (**Figure 25**) that depicts the different connectivity levels.

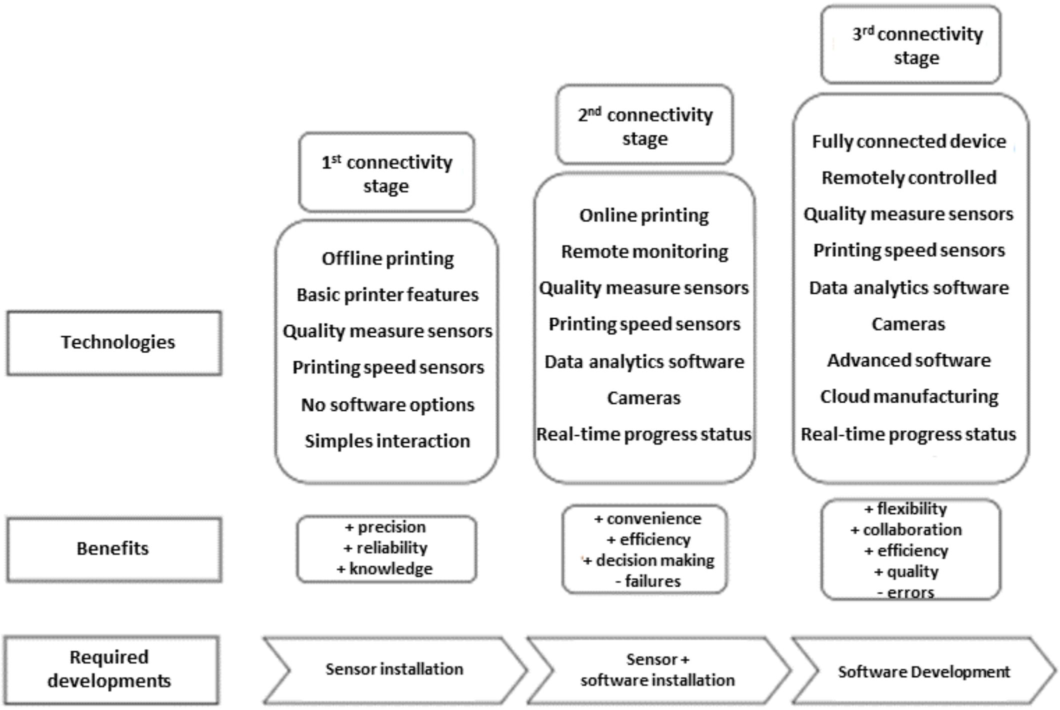

Figure 25. 3D printers IoT Degree of Connectivity benefits and technical requirements

These stages describe the normal evolution seen in 3D printers, beginning with stage 1 of IoT integration, when just printing quality is measured, and progressing until stage 3, where the device is fully connected and integrated with software. The gathered benefits from transitioning from one stage to the next and the required developments are detailed. Reaching stage 1 entails mostly sensor installation. Stage 2 requires software installation, as remote control and data analytics software can be sourced from third parties, however certain printers already have in-house developments. Moving from stage 2 to stage 3 requires extensive software development since automating and improving these sensors requires a complex software system. Another update required to generate data and connectivity is cybersecurity. Data protection is essential to ensure security and safely gather data.

These stages are intended to represent the generic framework that can be used in an industrial setting. By describing a generalized version of these stages this aims to create a framework for integrating IoT technologies into industrial machinery. This way, business can improve the efficiency, quality and flexibility of their machines. This framework acknowledges that the ideas of IoT integration, data collection, and remote monitoring can be useful in a variety of industrial sectors.

Similarly, it is possible to leverage the benefits of IoT integration in manufacturing so that industries beyond 3D printing can get more streamlined processes and data drive operations.

4.5 Organisational changes

Organisational changes are a part of the requirements to successfully integrate IoT technologies. There are different types of changes that need to occur in order to pursue technological integration in various areas of the organisation, as suggested by the technology roadmapping frameworks [62].

1. Realignment of Investments: Introducing technological advancements to an organisation requires focus and investment allocation towards obtaining sensors, hardware and training staff in using these technologies. This represents a significant investment that can prove to be an obstacle to managers. It requires an overall mental shift into embracing technological transformation and redefine investment focus [62].
2. Data-Driven Decision Making: The data gathered by IoT devices can serve as a strong support to decision making. Structure data and analytic insights can add valuable inputs into managerial decisions. Thus, investments in analytical tools, data management and expertise are required as well as a focus in introducing data-based insights into decisions [62], [63].
3. Product Development Redesign: With the data generated from the products, the product development process gains a different outlook, as processes get more data-intensive and different benefits are exploited. Furthermore, the flexibility promoted by technologies favours more agile approaches, abandoning waterfall processes, which leads to the need for redesigning processes [62].
4. Organisational restructure: To promote technological advancements requires multiple areas of knowledge and collaboration between different departments including IT, R&D, and manufacturing. Multifunctional teams foster collaboration and cooperation between teams which is not achieved by regular functional settings. **Figure 26** represents these necessary organisational changes [62].
5. Customer Centric approach: The IoT devices allow to interact with customers and involve them into the product development process. Gathering customer feedback is crucial to develop successful products and meet the customer needs [63]. Thus, creating supportive communities and adopting a customer centric approach is essential [36], [64].
6. Enhance automation: Technology advancements from IoT allow to use data into implementing automation, increasing manufacturing process efficiency, accuracy, and productivity.
7. Rethinking Business Models: With the multiple advancements installed, there are new possibilities for different revenue streams or approaches to the market, such as subscription based or data monetisation. Exploring these ideas should be a part of the long-term strategy formulated by reevaluating existing business methods and capitalising on the new developments [62].

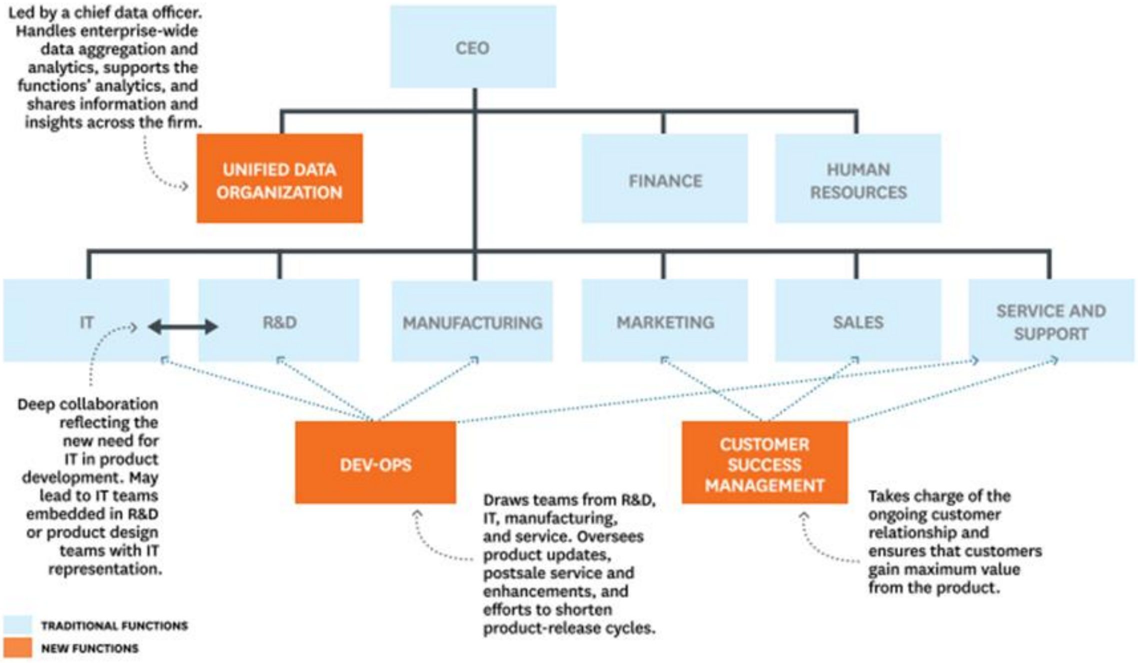

Figure 26. New organisational structure for companies integrating IoT technology [62]

Integrating technological advancements requires changes in the organisation culture, structure, processes, and strategy. Realising these changes can prove difficult as they often require big investments and a mindset shift from traditional operations. Although, embracing these technologies can help businesses produce better products, services and innovation.

From the required organisational changes described, three different organisational stages arise, as seen in **Figure 27**.

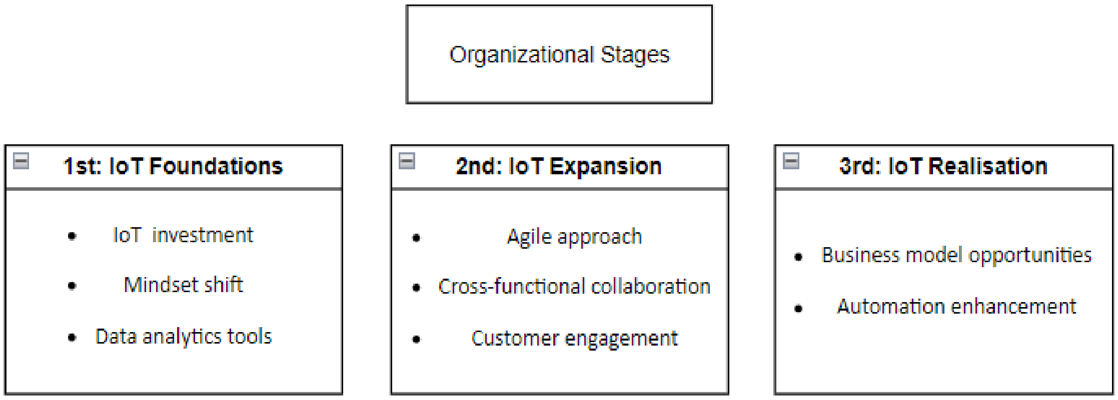

Figure 27. IoT organisational stages

The 3 stages can be defined as:

- **Stage 1: Establishing IoT Foundations**
    - **Realignment of Investments:** Create a long-term investment strategy that includes technological installation and staff training. Make sure the organisation focus is aligned with the technological change.
    - **Data-driven Decision Making:** Set up a data analytic structure throughout the company so that decisions can be supported by data.

- **Stage 2: Expanding IoT Capabilities**
    - **Product Development Redesign:** Evaluate the current structure of processes and apply agile and continuous improvement approaches.
    - **Organisational restructure:** Promote collaboration between departments and transition to multifunctional teams.
    - **Customer centric approach:** Use consumer generated data to improve products and foster customer interaction.

- **Stage 3: Realising IoT Potential**
    - **Enhance automation:** Use data insights to improve process efficiency, accuracy, and productivity.
    - **Reevaluating Business Models: C**onsider new revenue streams such as subscriptions and data monetization.

These organisational change stages are aligned with ISAEP key activities, reviewed in literature [50], to form a successful technological roadmap. Stage one focuses on building the foundations to introducing IoT technologies, stage two requires more organisational restructuring to successfully gather benefits from data generated and stage 3 promotes other areas of development.

The characterised changes require different expertise to be successfully implemented. Installing hardware devices require mechanical and electronic expertise, and the collaboration between these areas to ensure its right functioning. Furthermore, to identify the necessary technologies and design a long-term technological strategy, experts should have a deeper understanding of the IoT applications in the field. Along with these capabilities, strategic investments require business and financial planning skills to ensure a solid development. Data analytic tools require the knowledge of data analysts and data scientists to ensure a structured data architecture of systems, so that data is mapped and easily accessible.

Structural changes in the organisation processes and teams require project management skills to lead cross-functional projects and implement agile approaches. These managers can ensure the successful implementation of the IoT technologies. With the big data collection, data governance becomes critical in assuring data quality and compliance, thus appointing a Chief Data Officer (CDO) can give the necessary structure to the company in dealing with large amounts of data [62]. As IoT features evolve, network expertise is required to install remote monitoring and cloud manufacturing features into the machines and to develop an interactive platform with consumers. These platforms and interactions whit consumers should be coordinated by customer success managers, bridging the gap between the technology and the user requirements. With the enhancement of automation capabilities, computer science and software engineers are crucial in developing the software required to manage data and automate machines. Furthermore, industrial engineers can contribute to optimise processes and ensure effective automation.

The identified areas of expertise are reflected in the different stages as depicted in **Table 13**.

Table 13. Stages of Organisational Transformation and Corresponding Expertise Areas

Organizational stages	Ares of expertise
1st stage	Mechanical and electronic knowledge
	Strategic business and financial skills
	Data science expertise
2nd stage	Project managers
	Costumer success managers
	Data governance
3rd stage	Software developers and computer science engineers
	Control systems and industrial engineering

Although, software development knowledge is here represented at the third stage, it depends on when these developments are introduced to the machines. These different areas of expertise ensure that the process of organisational change and technological integrations is guided by qualified professionals, promoting its success and covering all aspects of the process.

These organisational steps can be integrated with the technological insights presented in the previous chapter to form a more comprehensive framework, which will be investigated further in the following chapter.

4.6 Framework Consolidation

The discussed viewpoints on costumer characterization, technological integration and organisational changes complement each other to form a comprehensive framework that helps companies guide their technological journey.

These fields are a part of a business foundation and are critical to the construction of this framework that aims to be a decision support model for managers.

Understanding the customer needs is crucial to develop successful products and remain competitive. The costumer centric approach integrated in the framework ensures that these steps attend to a consumer-focused market. It also promotes the interaction with consumers, giving business a critical tool to incorporate customer perspectives into their products and developed strategy.

Meanwhile, the technological aspect of the framework provides guidance in the integration of IoT technologies, which are critical in today’s fast paced markets. This can considerably improve the companies’ operations although it requires a substantial change in its core. This change, revised in the organisational restructuring aspect, is profound and affects workflows, the company’s culture and structure. The successful implementation of this framework helps companies to evolve and remain competitive.

Initially it was identified consumer preferences and priorities in respect to 3D printers. This was critical in developing a characterization of several 3D printer models with the end user in mind. Consumers may be divided into multiple categories, each of which places varying degrees of importance on specific printer qualities. These characteristics include price, quality, speed, connectivity, ease of use, reliability, and efficiency, as well as other potential technical upgrades that some printers may feature.

Different 3D printer models on the market were examined to identify various features, price points, and intended target markets.

According to their price points and features printers were aggregated into 3 different groups. The budget printers, professional and high-end, which offer different features to different audiences. Due to the higher range of connectivity features, the professional printer’s group can be subdivided into further subgroups. This gave a general outlook necessary to then review aspects of technology integration.

The connectivity analysis of printer models entailed reviewing different types of technologies implemented in 3D printers such as sensors, software capabilities and automation. Furthermore, It was examined the stages at which these technology features were introduced and evaluated the benefits of their integration.

The schematic depiction, of the flow of information from devices to the user, demonstrated how the data is collected and transformed into useful information and insights that support decision making. This analysis allowed to divide the technology features into three distinct stages of connectivity, identifying the benefits and requirements for each. These stages can be used to form the distinct subgroups within the professional printers' category, due to the extensive range of available features.

The organisational aspect complements the requirements analysis in terms of changes in the organisation. This entails changing the company mindset towards investments, decision making and business proposition, to fully explore the benefits of these technologies.

The diagram below presented in **Figure 28** represents the followed process to develop this comprehensive analysis.

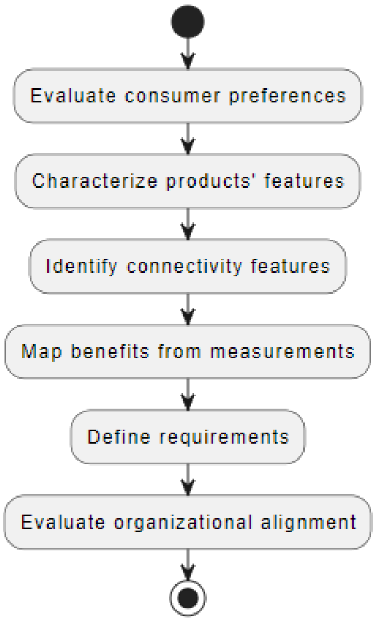

Figure 28. Steps followed to analyse the case study.

These sequential steps are consistent with the conclusions of the literature review on the key success indicators in product development processes.

The importance of developing a well-defined strategic strategy, encouraging customer collaboration, gaining top management support, and implementing a flexible workflow have all been identified as essential success elements, and incorporated into the research [23], [28].

Furthermore, these steps align with agile approaches as they emphasise the need of consumer interaction throughout the product development journey, promote iterative processes and continuous improvement [31], [39].

The integration of consumer insights is also encouraged by the collection of user generated data promoting a customer centric approach.

The analysis of a case study makes the findings generated from this framework more specific and practical when compared to a generalised analysis [23].

Having reviewed all these topics, it is now possible to integrate them into a comprehensive framework. To assess the different levels of connectivity the two extreme ends can more easily be defined. On one hand, a printer that offers the most basic functions to operate, on the other hand, a level with state-of-the-art industrial printers with fully connected product and with the highest quality standards.

Table 14 presents the characterisation of these two levels.

Table 14. Level 1 and 5 characterizations

Level 1	Level 5
Low Quality Basic mechanic features No data collection No connected devices Single area of expertise Functional organizations	Top quality High sensorization Data collection Data visualization Fully connected product Automated Remotely controlled Real-life stats tracking Software development Multifunctional team Multiple expertise areas Highly efficient Complex system

The first level includes the most affordable printers, which have basic mechanical functions but no data collection capabilities and a simple interface. These budget printers are primarily targeted at home users and beginners. The highest level of IoT integration reflects the market's premium models of customised printers that have top-notch quality and full connectivity, built to perform in industrial settings.

Combining insights from the perspectives discussed previously, the first level would also represent the stage requiring the least expertise for both development and operation. In this context, the organisational structure required for developing such a product would typically follow the functional model.

Meanwhile, the models at level 5 require multiple areas of knowledge and a more agile and flexible organisational structure that integrates multi-functional teams.

The models in between represent the previously recognised range of professional printers, with a greater variety of features than the budget-friendly versions.

Taking the previous analysis, technological features can be differentiated into 3 levels. Models at level 2 already include some connectivity that distinguish them from level 1. Between level 4 and 5 the complexity and extensive developments required to achieve and enhance automation, at level 5, separates them.

Ranging from 2 to 4 these levels can be consolidated into **Table 15**, which includes the various advantages, requirements, organisational changes, and areas of knowledge from the preceding chapters.

Table 15. IoT integration levels

	Level 1	Level 2	Level 3	Level 4	Level 5
Quality	Low	Medium Quality	Medium Quality	High Quality	High Quality
Speed	Low	Medium speed	High speed	High speed	High speed
Sensors	-	Quality and speed sensors	Quality speed & camaras	Quality speed sensors & camaras	Quality speed sensors & cameras
IoT options	-	Sensorisation	Real-time remote monitoring; data analysis tools	Real-time remote monitoring; data analysis tools; cloud manufacturing	Real-time remote monitoring; data analysis tools; cloud manufacturing
Benefits	Simple interface	Precision; reliability; process knowledge	Convinience; efficiency; better decision making; higher success rates	Flexibility; collaboration; efficiency; Quality	Highly efficiency and precise system; Automated decision making
Organizational structure	Functional	Functional	Multi-functional	Multi-functional	Multi-functional
Required developments	-	Sensor installation	Sensor & software installation	Software development	Software enhancement
Areas of expertise	Mechanical; electronical	Mechanical; electonical	Mechanical; electronic; data science; software develop.	Mechanical; electronic; data science; software develop.; industrial engineering	Mechanical; electronic; data science; software develop.; industrial engineering

By consulting the table, companies can assess their current product level and visualize the next developments ahead.

Furthermore, they can identify the benefits they would gain from levelling up their products, comprehend the areas of expertise required to evolve and recognize the technological improvements necessary.

There are some specific measurements from the case study that are less intuitive to generalise. Speed and camera sensors are widely used in the 3D printing industry, although for a generalization of the application of the framework it can be consider its ultimate function, assessing production conditions and error detection.

Quality standards are distinguished between low, medium, and high quality, these should be adapted to the specific case analysed. Depending on the products produced, there can be higher or lower tolerances for quality standards. These tolerances should be set by product development experts with the user experience in mind.

The methodology followed resulted in this generalized framework, as depicted in the Figure bellow (**Figure 29**).

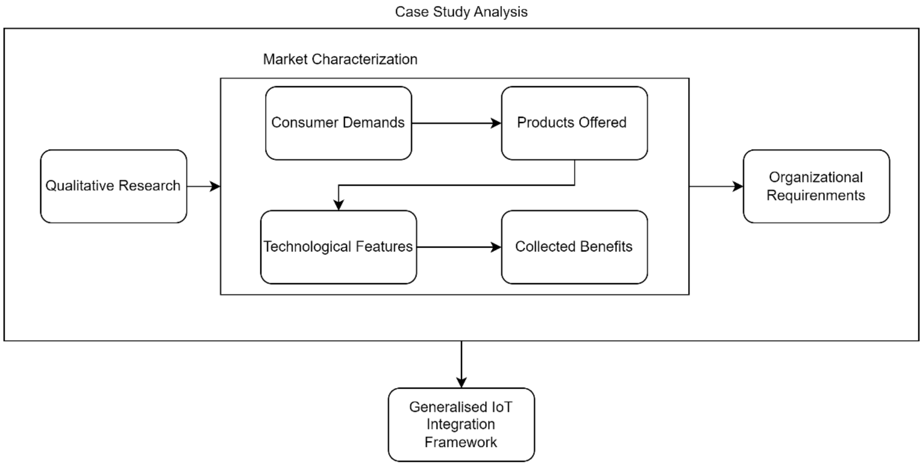

Figure 29. Resulting steps of the methodology.

The time and cost investments required for these organisational changes are also two essential variables to consider. Given the wide range of products and sectors, assessing the financial effects of these shifts is challenging. The amount of investment required varies depending on the existing organisational structure of a company, with some requiring bigger investments than others. Furthermore, the type of technology integrated is critical. Transitioning from level 1 to level 2 constitutes hardware installation, which is less expensive than the organisational adjustments required to go from level 2 to level 3. It is difficult to quantify these differences, due to the multiple different ranges of machines that are observed in the price spectrum. Using the previously identified price ranges, the development costs can be expressed as a multiplier of the overall cost of the product, indicating the cost increase from one step to the next. Placing the various levels on the defined scale to the different group of machines makes it possible to obtain the following price ranges seen in **Figure 30**.

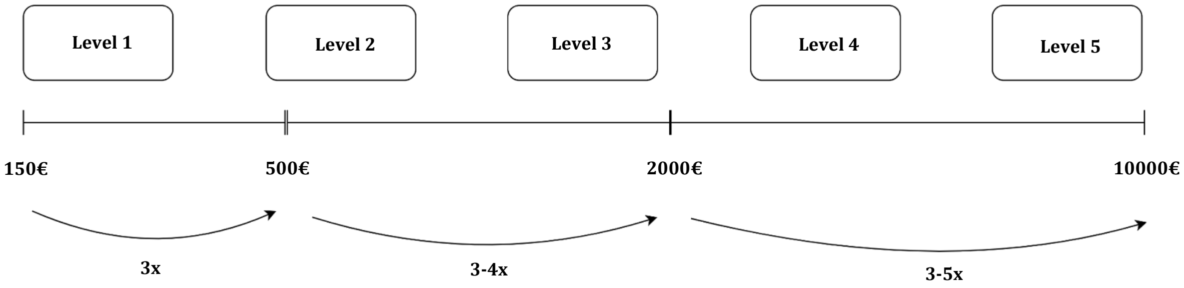

Figure 30. Price ranges for IoT levels of integration

The distribution of the different levels through the price ranges was done taking into account the range of requirements needed for each level. It was also recognised that when software integration becomes a factor, a considerable leap happens. It is important to note, however, that this attempt to assign value to the technological levels is rudimentary and lacks a full analysis or a solid foundation and it is tightly related to the specific case study. Companies should carefully assess their own specific cost of implementing technological changes. Nonetheless, this research provides some information on prospective implementation costs.

Due to the influence of machine quality requirements on pricing, restricting all three levels to the 500 to 2000€ range would be impractical. Transitioning from level 1 to level 2 would cost roughly three times as much as level 1 developments. Level 3 would necessitate a three to four times increase in investment above level 2. Level 4 would be around three times more expensive than level 3, whereas level 5 would be five or more times more expensive than level 3, or 1.5 times the cost of level 4. Although, investments to achieve level 5 integration are widely dependent on the level of software development. This cost distribution corresponds to the needs for each level, with the biggest jumps occurring when considerable technological integration and software development are required, notably from level 2 to 3 and 3 to 4.

The more complex the product the more time requires to be invested in its development. Generally, more resources, both in terms of time and personnel are necessary to support these improvements the more complex the product is. Analysing time requirements is difficult, due to their volatility. These are specific to each case, dependent on multiple factors such as resource allocation and the time objectives specified during the implementation of these changes. However, it is possible to observe that integrating software and implementing organisational changes require an extended amount of time when compared to other implementations. Software development requires specific technical expertise and organisational changes result from change in wide group of people. As a result, the use of a multifunctional organisational structure at level 3 and the installation of technological solutions are time-consuming implementations. Levels 3 and 4 require the most substantial time and resource requirements.

This characterisation of the different levels can be a significant tool for businesses looking to integrate technology. The model can be integrated into an iterative process where companies systematically assess their product's IoT integration, plan new advancements, and ensure that they continue to leverage IoT technologies effectively to keep up with evolving markets. **Figure 31** illustrates how companies can apply this framework to guide their technological advancements.

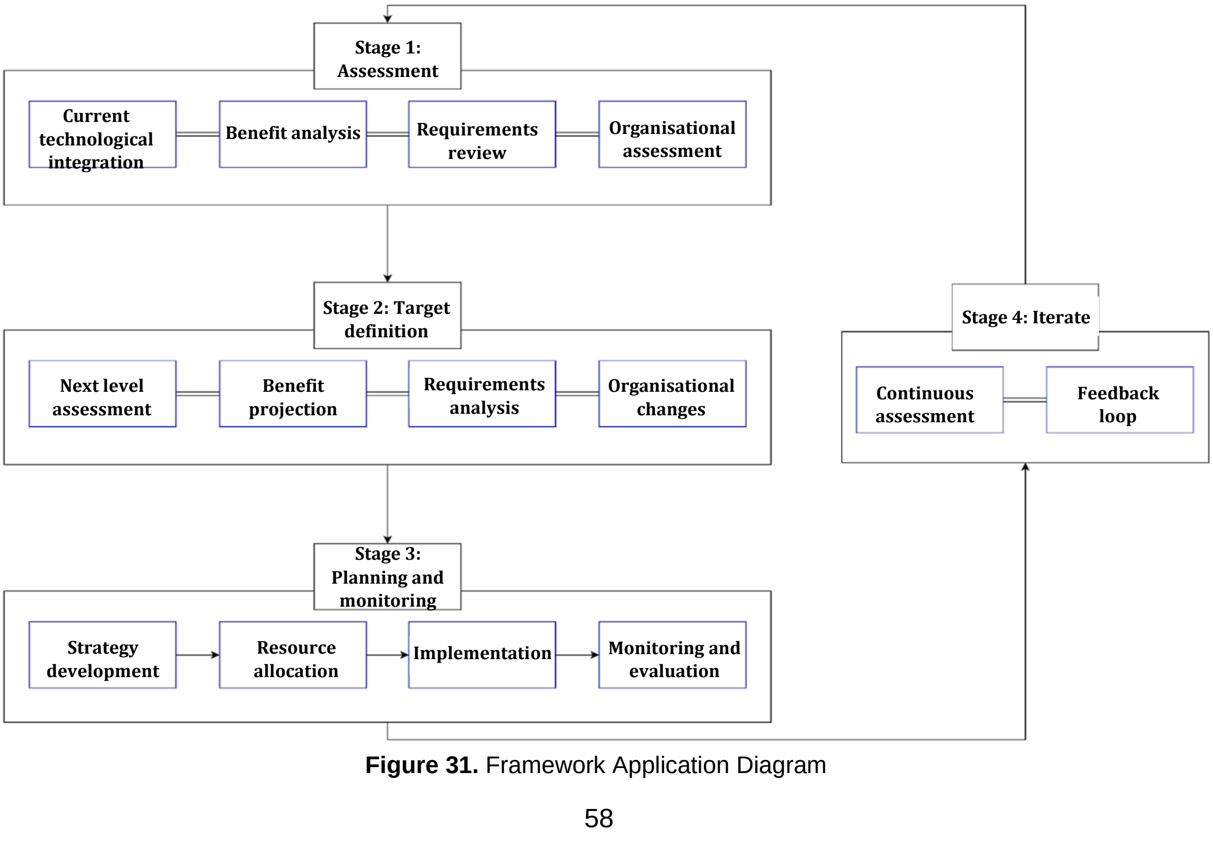

Figure 31. Framework Application Diagram

During the first stage there is a full assessment of the products and structural organisation. Begins by determining the existing level of IoT technology integration in the product and considering the advantages currently obtained from technologies. This is done by examining the device status regarding sensors integration, connectivity, and software capabilities, determining which areas of knowledge are currently in place. Furthermore, examining the company’s structure and capabilities allows to assess the current capacity to embrace new technological implementation.

In the second stage companies define the target goal for the technological implementation, assess the required technological and organisational changes, estimate the possible benefits of moving the product to the next level, determine the requirements that must be accomplished to advance to the next level and what additional areas of skill are required to advance, also, investigate the organisational changes that will be required to accommodate a higher level of IoT integration.

The third stage requires a specific workflow to plan and execute the implementations. Firstly, a clear plan that entails the requirements to move from one level to the next, including timelines, budgets, and resource allocation. Allocate resources accordingly to the revised plan. Implement the identified improvements required to advance to the next level. Lastly, continuously monitor progress and assess the efficiency of developments.

Fourth stage reveals the agile iterative processes. It entails continuously assessing the product's IoT integration level and adjusting as needed based on changes in technology, customer needs, or market expectations. This creates a feedback loop in which products use data and consumer insights guide future IoT integration decisions. To remain competitive companies must keep up with evolving IoT technology and market trends.

The study's findings emphasise the importance of high-level management involvement and the need for organisational mindset transformations. The resulting framework is similar to the sequential steps specified in the ISAEP roadmapping tool [50]. It starts with an analysis of the available technologies and identification of the current level of integration, followed by the acquisition of necessary technology, skills, and organisational changes. Then, it is realized the potential of these technologies and collected their benefits. Finally, the framework emphasises the significance of knowledge protection through iterative and continuous improvement procedures.

5. Conclusion

This dissertation contributes to the product development field regarding the integration of IoT technologies in the industrial realm. It provides a framework that helps organizations navigate technological transformations considering multiple areas.

The importance of the integration of consumer insights in the development of the framework was emphasised by literature. Thus, initial exploration of qualitative research and characterization of customer segments revealed essential in understanding consumer preferences. The most valued characteristics by costumers are cost, quality, speed, connectivity, ease of use, reliability, and efficiency, which are prioritised differently by the consumer segments. Multiple 3D printing models were analysed regarding their characteristics and technological aspects. It revealed that IoT play a critical role in improving process knowledge, flexibility, precision and quality. It was outlined the requirements for a successful IoT integration in terms of organisational changes, infrastructure and expertise.

The strategic framework, supported on these findings, is composed by five levels of IoT technology integration, from simple to fully connected industrial devices. Each level describes the requirements of specialised knowledge, technological improvements, and organisational changes, presenting companies with a roadmaping tool for their technological journey. Along the different stages it is required the installation of sensors to monitor key performance indicators and extract data, data analytics tools and software development to manage the data sets collected and promote data-based decision making, remote controlling and cloud manufacturing technologies to improve control over the process. These advancements require different areas of expertise, such as mechanical; electronic; data science; software development; industrial engineering, as well as a change to an organisational multifunctional setting. There are expected multiple benefits from these implementations. Increases in precision, reliability, convenience, process knowledge, efficiency, flexibility, and better decision making are attributed at each level.

It proved difficult to estimate the financial and time implications for each integration level. Although, it is pointed out that the most significant resources required occurred when transitioning between levels where software integration and considerable organisational changes were involved. The framework promotes the need for continuous improvement and iterative processes that increase adaptability and responsiveness to the market changing demands.

The developed work contributes with two takeaways. The framework described can be used by companies to assess their current IoT integration level, identify the potential benefits, and use it as a guideline to recognise the requirements to further improve their products. Another takeaway is that organisations can use the structured approach outlined to develop this framework and generate their unique product level characterization. Ultimately, this body of work provides a roadmap in the field of IoT technology integration aimed to help organisations improve their products and gained competitive advantage.

5.1 Future Work

After the conclusion of this dissertation, there are some recommendations for future lines of research that can improve the understanding of IoT technology integration in the industrial product development field. Validating the framework, using it in real-world case studies, studying the integration of different technologies, analysing the influence of time and costs, and evaluating the long-term advantages are all possible research directions. The future work recommendations intend to tackle some of the limitations as well as perfecting the work developed.

Initially, the validation of the framework should be done by conducting studies with industry experts and professionals in the product development field to ensure the robustness and effectiveness of the developed framework. Real industry case studies can provide valuable insights into the practical implications of applying the framework. Expanding the scope beyond the initial focus on 3D printing to include other industrial technologies can increase the applicability of the work developed and its relevance. Time and cost variables were underdeveloped in this research, a deeper examination of its implications associated with transitioning between integration levels complements the framework. Another potential study direction is evaluating the long-term impacts of IoT technology integration on industrial product development and the organisation success. Furthermore, the application of this framework can be evaluated within a sustainability perspective, as the increase in connectivity offers collaboration options. These future research recommendations can help to deepen the understanding and improve the applicability of the proposed framework.

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7. Appendix

Appendix A - Location of different sensors in a 3D printer