IoT technologies integration framework: A 3D printing case study

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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 dissertation 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 to characterize consumer preferences, existing IoT technologies, and organisational changes required. Preliminary interviews conducted with consumers identified as valuable characteristics like cost, quality, speed, connectivity, and ease of use. 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. This helps companies in improving process knowledge, flexibility, precision, quality, reliability, efficiency, and make more informed decision-making based on data gathered. Ultimately it assists to comprehend the requirements for advancing to next technological integration levels and what benefits to expect. It promotes a better understanding of consumer perspective, thus positioning their products strategically in the market and 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

1. Introduction

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]. Products now have mechanical, electronic, and software features, necessitating flexible, multifunctional teams for effective technological integration [2]. The current production paradigm emphasizes customer needs and intensive knowledge processes, relying on user engagement and flexible methodologies to achieve success and adaptability to the market [3].

Technological advancements, particularly in Industry 4.0 and IoT, are reshaping industries, requiring companies to quickly adapt to remain competitive. These advancements introduced connected devices that generate large amounts of data crucial to derive data-based insights in this consumer-focused market. Extracting value from the data generated has significant challenges requiring a holistic approach to strategic development, organizational changes, technology integration, and alignment with customer expectations [4].

Recent research has been concerned with integrating data collected into product development processes. This process aims to enhance decision-making, product quality, process flexibility, and increase consumer adoption [1]. Although, frameworks developed, in the product development field, lack practical specificity and relevance as literature favours theoretical approaches [5]. In a similar way and despite their value, technology roadmaps frequently lack integrated and comprehensive perspectives. It offers generic guidelines but lack case-specific and useful information for framework development [4].

This thesis addresses this significant gap in the literature by helping businesses navigate the complexities of the technological journey. To achieve this, it combines an integrated approach with the case study analysis, aiming to close this gap while assuring practical applicability. Based in the 3D printing industry, the case study attempts to relate itself to the industrial production setting and guarantee the development practical and valuable insights to industry developments.

The primary objective of this study is to develop a comprehensive framework that classifies products into distinct technological levels, offering a structured methodology and guide for enhancing product connectivity. This intends to respond to two research questions: What benefits do companies obtain when integrating IoT technologies in their products? And what steps companies need to take to improve their products connectivity?

2. Literature Review

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.

Three distinct manufacturing paradigms have developed in response to market changes [6]. Craft shops that employ skilled artisans that represent the hand-made manufacturing methods where each item is one-of-a-kind. Interconnected Industrial systems that use automation to achieve mass production and create standardised products. And post-industrial enterprises characterised by flexible resources and reliance on information intensive processes [6]. Currently, the paradigm is characterized by information-intensive processes, customer-centric products driven by data gathering and analytical insights, and the industry 4.0 revolution [4].

The manufacturing processes are supported on product development methodologies. These frameworks refer 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. The typical product development process is represented by a sequential model, from idea generation to product launch [2]. An analysis on different failure and success of product developments by each of its stages concluded that planning is of extreme importance to ensure the quality of the process and commercial success of products. Along the product development process, making changes gets increasingly costlier in development tasks as it reaches the final product [7]. Key success factors for successful product development include customer cooperation, senior management involvement, and thorough market research. Although these findings have not been properly converted into actionable recommendations, as project managers still make decisions based on their past experience and "gut feeling."

Although the initial product development framework is a sequential flow, it was found that companies operated with multi-functional teams and overlapping development phases, resulting in a rapid and flexible process. This approach enabled iterative testing of solutions, thereby minimizing potential errors in later stages and diminishing costs [8]. It promotes flexible environment from which organisations can benefit by loosening some of the rigidities that have grown through time [2], [8].

2.2. Agile Methodologies

Agile methodologies place a strong emphasis on flexibility, teamwork, and quick iteration, which promotes an ability to react quickly to altering needs and to deliver value frequently and early [3].

Cooper (2016) explored the benefits of a hybrid Agile-Stage-Gate model by integrating agile methodologies into stage-gate processes. The outcomes of this study resulted in a significant development speed gain of 30%, improvement of employee happiness and motivation and contributed to closing knowledge gaps [3]. Although, there are integration issues. The emphasis on adaptability results in less predictability, which makes managing resource allocation more difficult. Additionally, the lack of standardisation makes it challenging to create performance metrics. Furthermore, the dependence on customer collaboration can be challenging to manage [9].

Customer interaction is frequently regarded as a critical component in the success of product development and in agile methodologies. A thorough understanding of client requirements, the competitive landscape, and market dynamics is critical for new product success consumer [10].

Agile techniques are built on cross-functional teams and collaboration amongst team members with different skill sets [3]. The functional diversity of these teams expands the amount and variety of information accessible for product design allowing project team members to better understanding of the process increasing its performance. Furthermore, it allows to detect downstream issues before they occur, when these issues are typically smaller and easier to resolve [11]. These teams can be difficult to manage considering the different backgrounds. Tools like distance theory help bridge some gaps between team members or even customers and developers [12].

2.3. Industry 4.0

Industry 4.0 is revolutionising industries by combining breakthroughs in digital technologies and production processes. It investigates the integration of cyber-physical systems, the Internet of Things (IoT), artificial intelligence, and big data analytics to improve processes [13]. The benefits associated with these technologies are the enhancement of product quality, adaptability to market changes and efficiency through IoT's capacity to gather data, facilitating a deeper comprehension of processes, products and their life cycles. The integration of the customer in product development is promoted by these technologies. Challenges in integrating these technologies are mostly related to the cultural change required, the costs in the adoption of new technologies and the necessary infrastructure [13].

Industry 4.0 also introduced big data technologies. These represent the gathering and analysis of big volumes of data captured from connected devices. It revealed to play a vital role in the product development process as it influences key stages, such as idea generation, design, and testing, contributing to a customer-centric approach and data-based decision-making [14], [15]. Furthermore, research points out the positive impact of online user-generated content on product development contributing to increased product adoption and competitive advantage [14], [15]. Integrating data provides valuable insights into product usage, user challenges and areas for improvement, promoting customer loyalty and satisfaction. Managing data and aligning analytics with business goals are considerable challenges dragging down the potential of these technologies [14], [15].

To tackle the integration of industry 4.0 technological advancements that foster big data solutions, technology roadmapping aims to align technology integration with business goals, offering a systematic approach for identifying, prioritizing, and implementing technology developments. It involves characterizing the current state, analysing future trends, and defining a clear path for development. This helps organizations anticipate market needs, navigate technological advancements, and ensure efficient resource allocation [16]. The ISAEP framework focuses on the managerial implications of technological improvements, structured around three pillars: Strategy; Innovation; Operations. The time and effort required, the necessity for a solid base of information to support the framework and the difficulty in customizing the framework to fit a particular context are some challenges in adopting this framework [16].

3. Methodology

The methodology involves a comprehensive analysis of the 3D printing case study, integrated technology, user perspective, and organizational changes. This seeks to comprehend how IoT technology affects products and product development processes, producing insights that can be used across industries. The methodology followed resulted in the steps shown in **Figure 1**

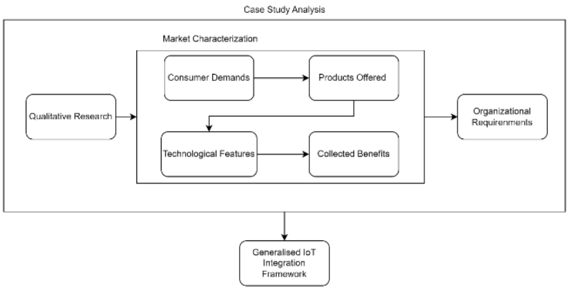

Figure 1. Resulting steps from the methodology

The study starts with qualitative research, aiming to integrate a customer-centric approach, by using interviews to collect customer insights on 3D printing technologies and survey the impact felt on their work. With the aim to characterize the 3D printing market, the examination of consumer groups deepens the understanding of distinct customer segments. In addition, the analysis of 3D printing models enhances comprehension of features and technologies, revealing the benefits and assessing the requirements. Combining these viewpoints, creates a framework that outlines the changes required at each level of connectivity as well as the expected benefits.

This methodology identifies necessary organisational changes, expected benefits at each connectivity level, and crucial connectivity features, although it's important to understand the limitations. The formulated framework derives from a specific case study, potentially limiting its applicability to other industries. The framework's limited scope could also ignore the broader effects of technology integration, particularly in terms of time and investment required.

The use of this particular case study relates to the wide range of connectivity features a machine can have to monitor its process, generate data and support software which makes this product an ideal case to study what is proposed.

4. Results

4.1. Qualitative Research

The qualitative research performed in the form of interviews aimed to gather relevant data that would enhance the research and offer insightful knowledge about 3D printing technology. The participants were selected from university students and alumni that currently interact or have used 3D printers. Participants stated their background knowledge relating this technology and their past experiences, their insights into the technological development, the impact of 3D printers on their work and future expectations for this technology.

From the collected insights some key takeaways were drawn. The participants emphasised the importance of having diverse machine features for different project demands. Precision is key as quality is a crucial factor for high standard printings. Technology developments were recognised, specifically in user interfaces, automation and control systems. Although developments are expected regarding user-friendliness, reduction of manual intervention, flexibility and the use of sustainable materials. Challenges identified included user friendliness difficulties and the complexity of integrating collected data into software to allow for automation development. The interviews revealed that rapid prototyping produces the most positive impact as it allows to quickly develop products for a more effective study, and also the flexibility machines provide help increase processes speed and efficiency. For future developments, participants expect improved automation through AI, user-friendly interfaces, a wider adoption of 3D printing technologies and increased variety of printing materials.

4.2. Market Characterization

The 3D printing market is characterized by the consumer group and the 3D printers' models in the market. The consumers of 3D printing machines are classified into 5 different groups regarding their characteristics valued and the purpose to which they buy the machine. The findings are depicted in **Table 1**

Table 1. 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 group has distinct priorities based on their specific needs and use which guides their printer selection. Due to this customer segmentation printer models are created to satisfy the requirements of these distinct consumer categories.

Different 3D printer models were analysed. The 22 different models were selected from the printers referenced by participants in the qualitative research and different websites indicating the most used models for different types of customers. The different features of these models were characterized regarding the most valued characteristics for the costumers. 3D printing machines can be grouped into budget printers, professional printers and high-end printers according to their price range. There is a positive correlation between price and incorporated features. Furthermore, the emphasis on connectivity decreases as the printer's quality level improves, as such, high-end printers prioritise industrial printing characteristics including precision, reliability, flexibility and automation while still providing connectivity choices. Connectivity tends to be more important for professional-grade printers, where a greater range of features can set them apart. These features include different sensors, cameras and remote monitoring options that to measure different performance indicators of the printing process such as printing quality, speed, error detection and material shortage. With these measurements a set of parameters can be designed to improve the process efficiency, flexibility and improve printing experience by providing data-based insights. **Figure 2** Illustrates the flow of information, from connected devices, through the printing process.

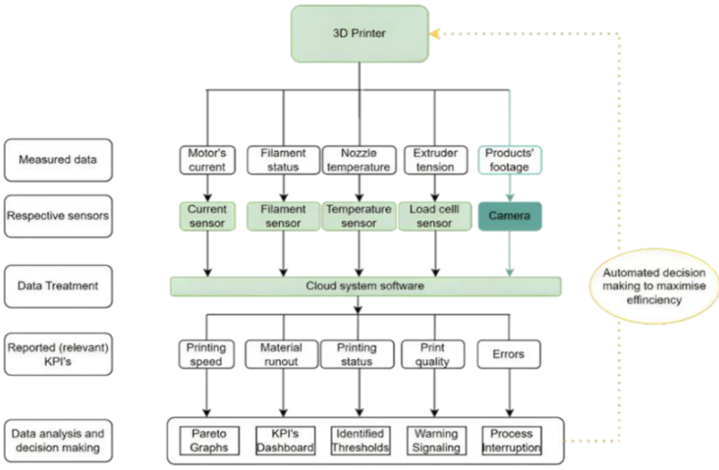

Figure 2. Schematic Illustration of Data Gathering with 3D Printing Sensors

This data is subsequently processed by software and cloud technologies, resulting in the generation KPIs 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. The advantages of incorporating various sensor types and different technologies into the printing process are illustrated **Table 2.**

Table 2. Technology integration and benefits

Measurements	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

These generic measurements and technologies are expected to be extendable to other types of products.

These technologies require the installation of sensors and software to operate and realize their benefits. In the analysed models, the technological integration in lower to higher end printers initiates with installation of sensors that improve quality, control over the process, and enhance data collection. Followed by the implementation of printing speed sensors and process interruption measures to allow remote monitoring options. Then, 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 development of software to orchestrate these functions with precision and efficiency.

4.3. Organizational Changes

The organisational aspect of the technological integration entails the expertise and organisational changes required to embrace the developments. As integrating IoT into products demands a total change of the organisation's culture, procedures, and strategies, in addition to technology improvements. Accepting these changes positions businesses to prosper in the IoT era, produce greater products and services, and open up new possibilities for development and profitability.

It is clear that a well-thought-out long-term strategy should include different important organisational changes. Realignment of investments towards technological implementation; adopt data-driven decision making; redesign of the product development to a flexible setting including agile methodologies; restructure organisation from functional divisions to multifunctional teams; take on a customer-centric approach with customer collaboration; enhance automation of repetitive processes; lastly rethink business models with the new integrated technologies. These steps are grouped into three stages identified for organisational changes during the integration of technologies: establishing IoT foundations; expanding IoT capabilities; realising IoT potential.

There are also different expertise required to advance through each stage. The first stage requires mechanical and electronic knowledge to instal sensors, strategic and financial skills to design a long-term strategy, and data science expertise to manage and extract relevant insights from gathered data.

The second stage requires project management skills to integrate agile methodologies and cross functional teams, costumer success managers for a customer centric approach, and data governance knowledge to ensure data quality and compliance. The last stage requires software development and industrial engineering skills to optimise industrial processes and ensure effective automation.

4.4. Framework

The consolidation of the different aspects reviewed result in a comprehensive framework that companies can follow to oversee technological integration. Integrating the consumer, technological and organisational perspective contributed to a consolidated overview of the technological integration process. The 5 IoT integration levels are characterized in the table (**Table 3**).

Through this framework, companies can examine their existing product standpoint and visualise the subsequent levels by referring to the table. They can identify the benefits of each level, recognise upcoming technology characteristics, comprehend the essential areas of competence, and pinpoint critical technological developments by doing so.

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 evaluation process. Companies can systematically assess their product's IoT integration, plan for advancements, and ensure that they continue to leverage IoT technologies effectively to meet evolving consumer demands and industry standards.

Table 3. 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

5. Conclusion

This research responds to the initially formulated questions. It details the benefits companies can expect when implementing technological improvements at each stage. Furthermore, it characterises each level of connectivity with the technological integration, organisational change and expertise required to enhance their products' connectivity. The developed framework is aimed to support managerial decisions by business looking to integrate technology developments. Businesses can use the framework to assess their current IoT integration levels, allowing them to quickly position their products and identify the additional benefits available by improving their connectivity. Organisations can use the information methodically by following the structured approach outlined. For organisations desiring a more in-depth examination of their processes, the steps utilised to establish this framework help to generate their unique product level characterization. This study provides a roadmap and a guide in the field of IoT technology integration. It aims to promote the integration of IoT technologies, improve products, and help companies gain competitive advantage in an increasingly connected world. Some limitations to this study are recognized. The formulated framework derives from a specific case study, potentially limiting its applicability to other industries; it is not validated by product development experts neither was put to practice to reveal its benefits in an industrial environment; the framework's scope is confined to the areas referenced, and the broad spectrum of technological integration's impact on a company is not comprehensively analysed.

5.1. Future work and recommendations

Future work should firstly focus on validating the framework by conducting studies with industry experts and product development professionals to ensure its robustness and effectiveness. Furthermore, applying the framework to real industry case studies can help to derive valuable insights into the practical applicability and effectiveness of the framework in different environments. Other recommendations regard the scope of the work developed. Beyond the initial focus on 3D printing, the framework's scope can be expanded to include the integration of varied industrial technologies. Time and cost were underdeveloped subjects in the research, a comprehensive examination of the time and cost implications associated with transitioning between different integration levels complements the framework.

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