Assessing the effect of 3D-Printing on the economic pillar of sustainability: A causal loop model

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Abstract

Design phase in product development has a great impact on production cost. 3D-Printing, also known as rapid prototyping, is an emerging technology and has gained significant attention in high-tech industries in the past couple of years. It's a powerful tool that offers some opportunities in the design phase of products. While many research have already been carried out to figure out what this technology will bring in the product development process, little has been done on its impact on profitability as an economic indicator of sustainability through systems thinking approach. Therefore, this paper employed qualitative system dynamics methodology to identify effects of rapid prototyping utilization on profitability through multiple feedback loops. This research provides insights into the generic benefits and challenges of 3D-implementation into the industrial system.

Keywords: 3D-Printing, Sustainability, System Dynamics, Prototyping, profitability

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Introduction

In the last decades, economic dimension of sustainability has gained importance among high-tech industries in terms of cost reduction and rise in profitability (Knofius et al, 2017). Manufacturers seek to reduce the time-to-market and production cost without compromising innovativeness and quality (Le Bourhis et al, 2013). Prototyping and research on products and their parts is one of the main sectors that has great impact on economic sustainability (Schöggl et al, 2017). On average, 70-80% of production cost is determined by design phase (Favi et al, 2016).

Number of assembly parts is one of the main factors in the determination of product development cycle time (PDCT). This stage includes so many iterations and rework, assuring desired quality and reliability of components (Knofius et al, 2017). Decreasing number of assembly parts will lead to fast response to market demand and reduction in production cost (Elezi et al, 2010). Therefore, high-tech industries are required to utilize new technologies in order to gain competitive advantage.

Three-Dimensional Printing (3-D Printing), also known as Additive Manufacturing (AM) or Rapid Prototyping (RP) is the process of joining materials to make objects from Computer Aided Design (CAD) model data by adding layer upon layer of material, as opposed to subtractive manufacturing methods (ASTM , 2012). Although AM has existed for over 30 years, 3D-Printing adoption has proliferated in the past couple of years and captured the interest of both technology experts and the industrial managers, because Rapid Prototyping implementation in the product development phase has various impacts on manufacturer performance and profitability. According to Mohr and Khan (2015) this technology holds opportunities for new sources of profit and possibilities in product design.

RP utilization removes tooling requirements, therefore, reduces tooling lead-time and time-to-market (Khorram Niaki and Nonino, 2017). It also enables designers to try multiple iterations simultaneously without time or cost penalties. This can be used in order to improve quality of products, their durability and help companies to enhance their after-sale services (Attaran, 2017). One of the main aspects of this technology is mass customization of production, increasing customer satisfaction (Berman, 2012). Mass customization refers to fulfilling the needs of individual customers and integrating them as early as possible in the value chain (Attaran, 2017). One of the other main advantages of RP is design optimization of assembly parts. This will lead to consolidation of parts and reducing the number of assembling parts and material consumption. Lower assembly parts brings lower production cost, increasing economic sustainability. However, current limitations of AM that potentially minimize its utilization include higher material cost, lower precision compared to other technologies and relatively slow building speed (Berman, 2012).

Many researchers have worked on RP in different contexts. However, most of them focused on the technological aspects. There are few studies to provide insights about AM's economic and managerial feasibility. Hence, the acceptance level and penetration rate of additive manufacturing are still at a challenging level (Khorram Niaki and Nonino, 2017; Ashour Pour et al, 2019). In addition, the consequences of adopting this technology on economic pillar of sustainability are not well understood. Through literature review, we realized that there is no prior model for assessing the impact of RP implication on manufacturer performance, implicitly profitability. Thus, to understand the effect of rapid prototyping utilization on profitability, a system dynamics model was developed and presented in this paper. System Dynamics Causal Loop Diagram (CLD) was built to identify major factors when implementing new technology. In this research, profitability which is the economic indicator of sustainability is measured through key variables, including time-to-market, production cost and customer satisfaction. This research contributes to the literature in RP technology by presenting a generic causal diagram, illustrating the benefits and challenges of RP utilization in the design phase of products through multiple feedback loops.

The effect of AM on profitability: review of the literature

The advent of AM technologies presents a number of opportunities for researchers in various fields. This study seeks to explore the specific research domains of RP in the area of manufacturer performance and profitability which is one of the economic indicator of sustainability. Lopez and Wright (2002) demonstrated the impact of RP on design and the product development processes. The result of their study showed that RP involved consumers in product design that led to customer satisfaction. It also reinforced ergonomic aspects of the design and quality of products, because prototypes helped to discover design flaws in earlier stages of product development. Yang et al (2015) represented a redesign method using RP with the aim of reducing part count and improving product performance. An example of a triple clamp was studied to verify the proposed method. The result demonstrated that RP reduced 20% of part weight and number of assembly parts from 19 to 7. It allowed for better quality and less material consumption, increasing economic benefits. Gebisa and Lemu (2017) investigated the design optimization capability of RP through a case study of the jet engine bracket. The results showed the advantage of RP utilization in reduction of product development time, product weight (65%), material consumption and production cost. Prakash et al (2014) used Design for manufacturing and assembly (DFMA) and rapid prototyping process to re-design a fluid flow control valve. They made alternative prototypes through 3D printing for testing. Good quality, reduction of production cost and consolidation of parts were the outcome of this research. Tuck et al. (2008) highlighted the practical advantages of AM in product design. The results showed the effect of RP utilization on the production in terms of time, cost and mass customization. Khorram Niaki and Nonino (2017) investigated the impact of additive manufacturing on business competitiveness through an exploratory study using multiple case research methodology. The findings indicated that implementation of rapid prototyping increases competitiveness and productivity of firms. This will also enable production of more complex customized products, increasing customer's satisfaction. They also reported less material consumption in production. Collins et al (2016) developed the prototyping process, in the product development phase, to overcome design constraints of a mountain bike through rapid prototyping. They reported better quality, performance and light-weighting, increasing consumer's satisfaction. Dudek and Zagórski (2017) compared cost and energy efficiency of selected methods of additive manufacturing with traditional methods of manufacturing parts. The results indicated that 3D printers are more energy-efficient than other manufacturing technologies. They emphasized that 3D printing can be used efficiently on the basis of batch size, element size, complexity, and material requirements. Vinodh et al (2009) investigated the practical implications of the 3D printing technology for promoting agility. The results indicated that this technology can quickly respond to customers’ dynamic demands due to reduction of product development cycle time. 3D printing enabled product designers to make a prototype in just few hours. This guarantees an increase in innovation, speed and quality, higher profitability and enhanced competitiveness.

System Dynamics Modeling

System Dynamics (SD) is a computer based simulation modeling methodology for analysis and problem solving; it's a tool that helps decision makers better understand the feedback structure in complex systems. It was originally developed by Jay Wright Forrester, during the mid-1950s, for the investigation of industrial systems with the aim of improving the understanding of dynamic complexity (Zwicker, 1980). SD has various applications and has been widely used in various socio-economic, financial, cost estimating, marketing, manufacturing and supply chain studies (Sterman, 2000).

There are some steps in system dynamics modeling:

- Define the problem: it is important to define the system problem clearly.
- Determining the important variables: the important variables are the key variables that the model seeks to improve them.

- Developing a dynamic hypothesis and causal loop diagram: this is used to map the cause-effect relationship between different variables within the system.
- Developing stock & flow: a quantified system dynamic model is built by translating the causal diagram to stocks and flows and their corresponding mathematical definitions.
- Testing and validation: simulate model in software and apply different scenarios (Sterman, 2000).

This research applied qualitative system dynamics approach and provide causal loop diagram for the following reasons:

First, although previous research mentioned many advantages and disadvantages for application of this technology, system dynamics can easily demonstrate which parameters in a system have enough ability to affect the whole system. In this way, system behavior will alter by changing those parameters. Second, multiple feedback loops can produce an unexpected system behavior which is different from simpler systems. This is a significant advantage of using system dynamics in studying technical and social systems (Forrester, 1968). Third, system dynamics models can clarify and unify the knowledge about a certain system. According to Forrester (1961) a good system dynamics model is one that change the way people look upon a system. Fourth, the literature review on 3D-printing shows a lack of model based research that deals with economic aspect of sustainability. Thus, this study aims at contributing to the model based research by taking the above observations into account.

Causal loop diagram

Causal loop diagrams are graphical visualization and represent a feedback system. The use of causal diagramming is very important during the first stage of modeling in identifying key variables, their causal interrelations and the feedback loops. This diagram consists of variables connected by arrows denoting the causal influences among the variables. These relationships can easily be shown by + and – , showing the direction of change one variable will cause to the other variable (Sterman, 2000).

In this section, we determined the composing elements of the simulation system and the causal connections among them based on an extensive review of the literature on 3D-printing. The causal diagram is presented in figure 1. Vensim PLE software (version 7.2) is used to draw causal loop diagram.

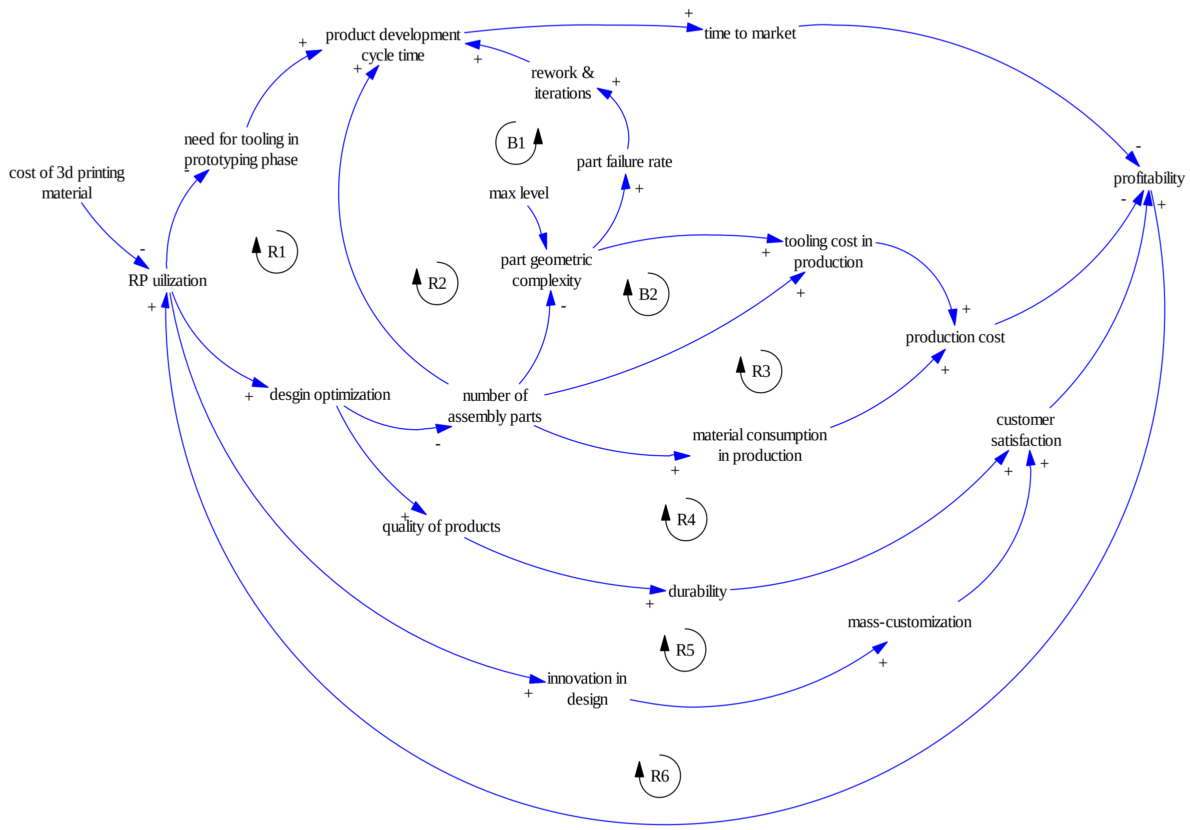

Figure1. Causal loop diagram

Model Description

The entire model serves the purpose of developing a model of describing the effect of RP utilization in the design phase on business profitability as an indicator of economic sustainability and identifying major points. This section describes eight loops in details (The loops in the model are shown explicitly in the following table 1).

R1: Benefits of eliminating tools

As RP Technology is implemented in the system, it requires no tooling in prototyping phase, which means that fully functional components directly produced by 3D-printing that eliminates tooling requirements. So, the long lead time for the delivery of tooling can be avoided. This leads to reduction in product development cycle time (PDCT) and time-to-market (TTM). TTM is the length of time taken in the product development process from product idea to the finished product. It is critical for high-tech industries to ensure that their innovations reach consumers quicker than competitors. This will increases their profitability. The higher profitability will increase the investment in technology adoption and rate of RP utilization. It should be noticed that high cost of material used in 3d-printing is one of the main limitations of this technology that potentially minimizes its utilization.

R2: PDCT reduction through design optimization

As RP utilization increases, so does the design optimization. The major advantage of AM is the freedom of design since it offers the production of parts with unlimited geometry complexity. AM makes it possible to create features which are not possible by conventional method and designers can consolidate many components into a single complex part. Therefore, the higher design optimization is, the lower the number of assembly parts. Then, product development cycle time will decrease. Other causal relations are the same as pervious loop.

B1: Disadvantage of reduction in number of assembly parts

As RP utilization increases, so does the design optimization. The higher design optimization is, the lower the number of assembly parts, which increases part geometric complexity. Higher complexity brings more rework and iterations to resolve it (Notice that, there is a maximum level of complexity based on conventional manufacturing capacity). More rework increases PDCT. This will lead to increase in time-to-market, which reduces the profitability.

B2: Effect of part geometric complexity on tooling cost

As RP utilization increases, so does the design optimization. The higher design optimization is, the lower the number of assembly parts, which increases part geometric complexity. As the level of complexity increases for each part, tooling cost increases as well. This will lead to increase in production cost and reducing the profitability.

R3: Tooling cost reduction through number of assembly parts

The decreased number of assembly parts through design optimization will decrease tooling cost in production, because consolidation of parts leads to reduction in number of different tools required in production.

R4: Reduction of material consumption

Once the number of assembly parts decreases, material consumption in production decreases too. This will lead to decrease in production cost and increase in profitability.

R5: Design optimization benefits

Design optimization through RP utilization increases quality of products that leads to increase durability of products. As durability increases, the customer satisfaction enhances also. Through literature review, there is link between customer satisfaction and profitability.

R6: Innovation in design benefits

Increased RP technology implemented leads to increased innovation in design, which enables more mass customization opportunities. This process is a mean to meet the specific requirements of customers, thereby increasing customer satisfaction and profitability[2].

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[2] Profitability is the sum of time to market, production cost and customer satisfaction. Please note that time to market and customer satisfaction should be calculated from monetary perspective.

Table1. Causal Loops Diagrams in details

Loops	Name	Remark	References
R1	No Tooling Benefits	Reinforcing loop	(Berman, 2012; Holmström, 2017)
R2	PDCT reduction through design optimization	Reinforcing loop	(Yang et al, 2015; Gebisa and Lemu, 2017)
R3	tooling cost reduction through number of assembly parts	Reinforcing loop	(Attaran, 2017; Yang et al, 2015)
R4	reduction of material consumption	Reinforcing loop	Knofius et al, 2017; Holmström, 2017; Chua et al, 2010)
R5	design optimization benefits	Reinforcing loop	Prakash, 2014; Oettmeier and Hofmann, , 2016)
R6	innovation in design benefits	Reinforcing loop	Mohr and Khan, 2015; Attaran, 2017)
B1	disadvantage of reduction in number of assembly parts	Balancing loop	Knofius et al, 2017; Pour and Zanoni, 2017)
B2	effect of part geometric complexity on tooling cost	Balancing loop	Knofius et al, 2017; Hopkinson and Dickens, 2001)

Discussion and future research direction

Design phase is the first step in any manufacturing process in which most of the important decisions are made, affecting the economic dimension of sustainability (Prakash et al, 2014). 3D-Printing as an emerging technology has the potential to affect key variables related to profitability. Although previous research have implicitly referred to the major benefits of this new technology for manufacturer performance, to the best of our knowledge, this is the first study to develop a model representing RP utilization impact in the product development phase and identify key variables, relating to profitability and economic aspect of sustainability. For this purpose, through an extensive literature review, a causal diagram was provided.
System dynamics approach is beneficial in predicting the effect of technology implementation on manufacturer performance; the causal model illustrated how profitability is affected by RP utilization through different feedback loops. The main contribution of this study is that it helps scholars, researchers and practitioners to understand a system from a wider perspective by applying SD methodology. In terms of managerial contributions, this study provides insights into the generic benefits and challenges of 3D- implementation in the industrial system.
Rapid prototyping has the potential to enable high-tech manufacturers to reduce their product development time and improve designing processes in terms of increasing quality and innovation of products and reducing the number of assembly parts. It can also reduce production cost through decreasing tooling cost and material consumption due to consolidation of parts. This technology facilitates production of products that can be individually customized, increasing customer satisfaction. These benefits can enhance profitability. Although rapid prototyping has some limitation and there are some challenges in this process, experts believe that it will keep growing at a fast pace and influence many high-tech industries. Moreover, the simulated model in software may produce different behavior, especially from one industry to another. For example, although consolidation has major benefits (such as reduction in material consumption, PDCT reduction), complex parts are often difficult to produce with conventional manufacturing, thereby increasing tooling costs and production difficulties (Loop B2). In addition, this will take more time and reworks to resolve this issue (Loop B1). However, it is

also possible that the increased profitability through the other six reinforcing loops justify the disadvantages and challenges of RP utilization. Therefore, further studies are required to provide Stock & Flow model and simulate it to figure out which parameters in a system have enough ability to affect the whole system. Simulation adds value to policy analysis because this will bridge the gap from structure to behavior and predict the effects of the variables over a period of time. This is important for strategic planning and decision making as well as for future research.

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