Sustainable development analysis of design and manufacturing integration: A system dynamics approach

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Abstract: The issue of the sustainability of design and manufacturing is dynamic, comprehensive and complex, and has always been a subject of discussion for scholars. This paper focuses on the sustainable issues of design and manufacturing and attempts to establish a system dynamics model combining design and manufacturing sustainability (CDMS). Through the method of system dynamics, Vensim software is used as the research tool, and the functions and influence proportions of the influencing variables are substituted into the model and then calculated. The information feedback mechanism and the causal cycle principle are used to simulate the development state of design and manufacturing. The results show that CDMS can smoothly present the interaction between design and manufacturing, and the variables are related to each other, showing the advantages of the CDMS model in analyzing the sustainable development of design and manufacturing. The research can provide further reference for follow-up research and practical application.

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PUBLIC INTEREST STATEMENT

The purpose of this study was to analyze the sustainability of design and manufacture by means of system dynamics and to determine the relationship between variables and the impact value through the discussion of industry experts in a focus group. It solved the problem of unmeasurable soft variables (such as designer responsibilities, design strategies, environmental awareness, etc.) and laid a foundation for future research. It should be pointed out that this paper put forward a proposal for the research method of system dynamics for sustainable design and manufacturing, aiming at promoting the discussion of this important topic and encouraging readers to provide feedback to the author in order to support the further development of this research.
1. Introduction

Historically, industrialization has been one of the main causes of pollution, as it has ignored environmental issues and led to unsustainable production modes. Based on this situation, a sustainable manufacturing system should be established (Carvalho, Chaim, Cazarini, & Gerolamo, 2018). The core value and role of design in the manufacturing industry are becoming increasingly significant (Deutz, McGuire, & Neighbour, 2013). Based on the subversive innovation of green design, the new manufacturing era provides a complete technological guarantee, and the construction of modern specialized factories with automation, informatization and intellectualization enhances the sustainability of manufacturing (Dace, Bazbazers, Berzina, & Davidsen, 2014).

Economic, social and environmental aspects have become the focus for enterprises sustainable development strategies and important indicators to improve the competitiveness of enterprises. However, previous studies on sustainable development have mainly focused on theoretical discussion (Chang & Cheng, 2019). The literature on sustainable development is expanding. Despite a large number of documents and problems related to sustainable development, controversy about this vague and multifaceted concept still exists, which makes the research on sustainable development extremely challenging. The system dynamics method can be applied to the problem of sustainability with low quantification requirements and trend responses (Nabavi, Daniell, & Najafi, 2017). It can intuitively analyze the relationship between various factors (Sahin, Stewart, & Porter, 2015). At the same time, through literature review, it is found that there are few studies on the sustainability of design and manufacturing. Based on system dynamics, the design thinking and exploratory research on sustainable development theory and manufacturing practice is not only of urgent practical significance but also of theoretical significance to the development of sustainable manufacturing theory. Sustainable development requires urgent fundamental changes in manufacturing systems. Manufacturing enterprises face global competition for sustainability (Giret, Trentesaux, Salido, Garcia, & Adam, 2017). Therefore, the main motivation of this study is how to explore the role of design and manufacturing through the method of system dynamics and how to pay attention to the effect of design and manufacturing on sustainable development.

This study analyzes the relationship between design and manufacturing and takes the sustainability of both at the core, constructing a systematic “design-manufacturing” logic system by means of system dynamics, studying the systematic flow chart of the relationship, explaining the quantitative impact relationship between design, manufacturing and sustainability, developing a model for systematically analyzing and evaluating the sustainable development of design and manufacturing, and establishing a sustainable system dynamics model (CDMS) including important variables related to design and manufacturing.

In this study, system dynamics is applied to uncertain design and manufacturing systems to assess sustainability. The following issues are discussed:

1. For unmeasurable variables, how should these be quantified as data inputs into system dynamics?
2. What variables have a positive impact on design and manufacturing variables on sustainability? What are the logical and quantitative relationships of these variables?
3. Which two key variables affect the sustainable development of design and manufacturing? Which has the stronger influence?
2. Literature discussion

2.1. Sustainable development of design and manufacturing

Sustainable development is an issue that should be actively explored and studied in all disciplines (Maruthi & Rashmi, 2015). Manufacturing has a significant impact on social, economic and environmental sustainability (Saad, Nazzal, & Darras, 2019). Sustainability is the basic requirement of the modern manufacturing industry to minimize the impacts to the environment and health and save energy and natural resources (Kishawy, Hegab, & Saad, 2018). With the development of the Internet and Internet of Things, manufacturing has entered a new era. Enterprises must find a new foothold to achieve the sustainable development of enterprise innovation and environment (Dace et al., 2014). Manufacturing is a part of production that reduces waste and waste emissions and increases economy and resource conversion. It reduces environmental through product design and process planning. The meaning of sustainable development means that every manufacturing process should consider storage resources for the next generation (Maruthi & Rashmi, 2015).

According to the literature of Kumar Mittal and Singh Sangwan (2014), Huang, Tu, and Hung (2016), the connotation of sustainable manufacturing includes the following aspects: reducing waste emissions, making rational use of the environment, producing green products and using degradable materials, recyclable components and non-polluting equipment (Kumar Mittal & Singh Sangwan, 2014) (Huang et al., 2016). The application of the concept of sustainable manufacturing has various advantages, such as reducing energy consumption, reducing or eliminating waste, improving product durability, achieving better health and safety conditions and enhancing the overall performance of manufacturing systems and processes (Kishawy et al., 2018).

In the product manufacturing stage, the main issues to be tackled include the relationship between materials and production and the steps of production (Huang et al., 2016). In order to make profits and create sustainable value for all stakeholders, the next generation of manufacturing needs to respond rapidly and economically to the changing market demands while minimizing adverse environmental impacts, achieving sustainable manufacturing based on the 6R (reduction, reuse, recycling, recovery, redesign and remanufacturing) and using more sustainable manufacturing processes and systems to promote the production of more sustainable products (Koren, Gu, Badurdeen, & Jawahir, 2018).

Sustainable design takes into account the environmental, economic and social impacts of the entire product life cycle. Sustainable design aims to reduce the environmental and social impact of products (Bhamra, Lilley, & Tang, 2011). Design helps to solve complex ecological problems and is also suitable as a source of solutions. The design concept is considered to be a method that may help to obtain a solution and contribute to sustainable development. Sustainable design is considered to cover all three aspects (technology, ecology and sociology), while ecological design usually considers only technical and ecological aspects (Shapira, Ketchie, & Nehe, 2017). However, a good design strategy is of great importance to the production process; that is, whether the production is environmentally friendly, including tangible and intangible factors, in order to make these factors consistent with environmental protection needs. Designers should strive to adopt appropriate methods to reuse and regenerate products (Huang et al., 2016).

2.2. Sustainable assessment of design and manufacturing

Most of the work on sustainability assessment in manufacturing is done at the product level or in specific processes (Saad et al., 2019). The possibility of the validation of design before mass production provides strong design support for sustainable factors in manufacturing and is the key link to achieve manufacturing upgrades (Ceschin & Gaziulusoy, 2016). When designing, whether the manufacturing process pollutes the environment and saves energy should be considered. The integrated design and production system can reasonably control the quality, assessment and the impact of environmental pollution on the process, achieve the goal of minimizing the impact on the environment and maximize the use of resources. At different stages of production, an integrated process model should be developed, and new evaluation criteria should be added to...
optimize the production process. In order to avoid the independence of a single standard, a pluralistic assessment should be carried out according to technical, economic and ecological standards. According to innovative design requirements, modern engineering systems (Maruthi & Rashmi, 2015) involving environmental and economic advantages of the entire product life cycle should be developed jointly. Systems dynamics associated with design methodologies, as with product service system design and design for social innovation, can help enhance the links between sustainability and realization, identify overlapping components and complement the weaknesses of both (Ceschin & Gaziulusoy, 2016).

The influence weight of some factors can be determined according to the experience and judgment of the designer. An acceptable level of sustainability can be found by appropriate optimization methods. The acceptable level of sustainability is defined by the experience and judgment of the designer (Kishawy et al., 2018). Hegab, Darras, and Kishawy (2018) proposed that sustainability assessment should be conducted in four stages: pre-manufacturing, manufacturing, product use and post-product use. Energy consumption, processing costs, waste management, environmental impact and personal health and safety should be taken as indicators of overall sustainability assessment, and the measurement methods of each indicator should be defined. This assessment algorithm can be flexible for each indicator’s distribution of different impact weight factors (Hegab et al., 2018).

Sustainability is based on three main objectives: economic growth, environmental protection and social responsibility. The impact of lean production on sustainability is very important (Henao, Sarache, & Gomez, 2018). Energy saving and emission reduction strategies are the key measure to promote the sustainable development of the manufacturing industry, namely to effectively improve energy efficiency and reduce waste emissions (Tseng, Tan, & Siriban-Manalang, 2013). An innovation-oriented lean approach is a key driver of sustainability, and its changes may significantly affect the sustainable results of manufacturing supply chains (Orji & Liu, 2018). Through literature research, the goal of sustainable development should be considered in design and manufacturing (Hegab et al., 2018; Henao et al., 2018; Orji & Liu, 2018; Tseng et al., 2013), as shown in Figure 1.

Sustainable manufacturing is essentially a complex systemic problem, and it is difficult to deal with the problem of sustainable manufacturing by existing complete methods, because these methods mainly deal with production and process, but do not emphasize the interoperability between them (Jawahir & Bradley, 2016). System dynamics provides an effective tool for
evaluating the impact of “design-manufacturing" sustainability. In the future, system dynamics will evolve into more specific methodological models to describe the impact of human behavior on the environment. At the same time, considering similar waste classification and the effective utilization of materials may have an important impact on the research results (Dace et al., 2014).

2.3. System dynamics and its application

System dynamics is a qualitative and quantitative analysis method (Sumari, Ibrahim, Zakaria, & Ab Hamid, 2013) which was proposed by Prof. Forrester in 1956 and is widely used in various fields (Ghaffarzadegan, Lyneis, & Richardson, 2011). Many scholars have used different methods and theories, such as statistical analysis theory, evolutionary game theory and innovation diffusion theory. However, complex relationships cannot be properly described by the above theories. Systems dynamics can explore sustainable problems by analyzing various aspects (Tian, Govindan, & Zhu, 2014). Other scholars point out that green information systems, especially footprint calculators, are promising feedback tools that can help people to adopt sustainable behavior (Buhl, Liedtke, Teubler, Schuster, & Bienge, 2019).

Sustainability is a complex problem that is interrelated with and affected by various variables. In order to explore the role and impact of various variables on sustainable development, this study used system dynamics as a research method. The specific reasons and characteristics are as follows:

1. The method of system dynamics modeling is developing and improving continuously. It is an effective method to study complex systems (Kim et al., 2019) (Sterman, 2018).
2. The system dynamics method is applicable to sustainability problems that require little quantification and can respond to trends (Nabavi et al., 2017), such as the sustainability analysis of design and manufacturing in this study.
3. The system dynamics method can be effectively applied to target-specific analysis and modeling (Nabavi et al., 2017) and can intuitively analyze the relationship between various variables (Sahin et al., 2015).
4. The system dynamics method can use empirical data to build models for the study of complex problems with insufficient data and low processing accuracy, which will not have a substantial impact on the study, but can still obtain the main information (Sterman, 2018).

System dynamics applies to the modeling of sustainable manufacturing (Kibira, Jain, & McLean, 2009). System dynamics can analyze the interaction of sustainability behavior. Its conceptual model solves the sustainability problem within manufacturing enterprises (Zhang, Calvo-Amodio, & Haapala, 2013). Existing product design practices lack effective methods to quantify the effects of uncertainty (Afshari, Peng, & Gu, 2016). In addition to operational management, organizational behavior, project management and market uncertainty, system dynamics is also used to analyze product design and development (Al-Kadeem, Backar, Eldardiry, & Haddad, 2017). When it involves product design, system dynamics is also the first choice for analyzing product and service design under different conditions, providing an appropriate method for the modeling of manufacturing systems for sustainability assessment (Zhang et al., 2013).

3. Research methods

Prof. Forrester, the founder of system dynamics, correctly demonstrated the validity of obtaining system dynamics data through expert interviews in his early years. He emphasized the importance of written materials. System dynamics data should not depend on numerical data, because numerical data are relatively fixed. Compared with expert judgments, numerical data can lead to variable limitations and result bias and may lead to errors or harmful policy recommendations (Forrester, 1980) (Sterman, 2018). This study identifies variables and defined variables through expert interviews, built logical models and implanted data into variables of the Vinsem model for operation. System dynamics understands systems by identifying the relationships among factors, uses structured models, allows decision makers to simulate systems and explore opportunities for improvement and helps decision makers predict alternatives to sustainability performance indicators for various systems (Zhang et al., 2013).
3.1. Expert interviews
Systemic dynamics can be studied through questionnaires, focus groups or interviews (Zhao & Zhong, 2015). This study interviewed a product design and development company in China. The company is mainly engaged in product design, product development and mold model design and invests in and produces independently developed products. The head of the company has won the leading talents in industrial design in the Ministry of Industry and Information Technology of China, the top ten outstanding designers in China’s industrial design and the top ten outstanding young people in Guanghua Longteng’s Chinese design industry. Firstly, we provided literature review data, interviewed company leaders and inquired about and recorded key variables affecting the sustainable development of design and manufacturing; secondly, we visited the company and viewed its products, conducted semi-structured interviews with design directors and engineers and established a logical model of system dynamics; lastly, relevant experts were gathered to discuss variables in order to construct a system dynamics model with quantitative relation.

Prof. Forrester, the founder of system dynamics, points out that researchers are encouraged to talk to professionals to obtain information about unmeasurable soft variables (Forrester, 1980). Therefore, this study uses focus group interviews to organize expert group joint analysis and discussion, scoring the impact values among variables and determining the numerical impact relationships among variables (e.g., designer responsibility, design strategy, environmental awareness, etc.). This study focused on the focus group, in addition to the basic professional knowledge of the study, mainly discussing four issues:

1. What are the variables that affect sustainable design and manufacturing?
2. What are the most important factors influencing sustainable design and manufacturing?
3. What is the relationship between variables?
4. What is the value of influence between variables?

The purpose of (1), (2), and (3) is to construct a logical qualitative model of system dynamics. Based on the first two questions, the purpose of (3) is to construct a system dynamics model with quantitative relationships.

3.2. Determine variables
We determine variables according to the main guidelines of Figure 1 in Chapter 2.2. When determining variables, (1) it is important to avoid the company’s choice and determination of variables without affecting the indicators; (2) as in Figure 1, which includes the main indicators of sustainable development rather than the ideal indicators of the company, one should avoid the company experts preferring the company’s desired direction when determining the variables of sustainable development; and (3) the determination of variables follows an important role in sustainable performance. Based on the above principles, 20 variables affecting the sustainable development of design and manufacturing were determined. Among them, 16 auxiliary variables, 2 rate variables and 2 horizontal variables were determined for further modeling and analysis in the system dynamics software Vensim. The descriptions of each variable are shown in Table 1.

3.3. Define variables
According to the research content and purpose, each variable was defined for further analysis.

3.3.1. Sustainable development
Sustainable development means that every manufacturing process should consider storing resources for the next generation (Maruthi & Rashmi, 2015), including economic, social and environmental objectives (Henao et al., 2018). This study focuses on the sustainable development of design and manufacturing.
3.3.2. Design strategy
Design strategy refers to a plan to gain competitive advantage through product design. In this study, the design strategy is a series of comprehensive and long-term strategies to achieve results in environmental protection.

3.3.3. Environmentally friendly design
The design takes into account the use of environmentally friendly materials in manufacturing, minimizing environmental damage during and after use and minimizing adverse environmental and social impacts (Howarth & Hadfield, 2006).

3.3.4. Product packaging
Packaging uses sustainability labels and environmentally conscious design (Cho, 2015). Good product packaging improves logistics efficiency, and the packaging materials and packaging methods reduce environmental impacts and minimize waste and pollution to the environment (Molina-Besch & Pålsson, 2016).

3.3.5. Design concept
The design concept plays an important role in the early stage of product development, which affects the development process and the success of the product developed. Essentially, design concept assessment is a complex multi-criteria decision-making process involving a large amount of data and expert knowledge. It is often imprecise and subjective (Zhai, Khoo, & Zhong, 2009).

3.3.6. Designer responsibility
Designer responsibility refers to the incorporation of sustainable development into design and is also related to broader social and economic impacts (Howarth & Hadfield, 2006). Product designers need to consider changes in users’ needs in the product life cycle (Afshari et al., 2016).

### Table 1. Design and manufacturing sustainability variables table

| Variable | Details | Type | Variable | Details | Type |
|----------|---------|------|----------|---------|------|
| SD       | Sustainable development | A | GR       | Green resources | R |
| DS       | Design strategy | A | ER       | Environmental regulations | A |
| EFD      | Environmentally friendly design | R | EAW      | Environmental awareness | L |
| PP       | Product packaging | A | EI       | Environmental impact | A |
| DC       | Design concept | A | EA       | Environmental agreement | A |
| DR       | Designer responsibility | A | CP       | Corporate profits | A |
| MT       | Manufacturing technology | A | HR       | Health requirements | A |
| MC       | Manufacturing cost | A | NR       | Natural resources | L |
| IA       | Innovative approach | A | PF       | Policy | A |
| PC       | Production cycle | A | SI       | Social impact | A |
| GE       | Green equipment | A | ECI      | Economic impact | A |
| EPR      | Environmental protection requirements | A |

Abbreviations: C stands for constants, A for auxiliary variables, R for rate variables and L for horizontal variables.
3.3.7. Manufacturing technology
Good manufacturing technology makes manufacturing systems more environmentally friendly, saves costs and promotes the development of environmental protection technology. In addition, good manufacturing technology should emphasize that it does not pollute the environment and damage the health of employees and residents in the manufacturing process (Kumar & Rao, 2018).

Manufacturing costs: Manufacturing costs include materials, processing, machine settings and non-production costs (Shehab & Abdalla, 2001).

3.3.8. Innovative approach
Excellent innovation requires a high level of innovation capability to create sustained success (Purwanggono & Amalia, 2019). Innovation methods vary in different areas. The innovative methods in this study refer to breakthroughs in green manufacturing, and also include creative methods related to the formulation of design problems and original concepts.

3.3.9. Production cycle
The production cycle refers to the total time from the beginning of production to the output of a product. In industry, this refers to the whole time of the product from the start of raw material production, through processing, to product completion, acceptance and storage.

3.3.10. Green equipment
Green equipment should be able to reduce waste emissions (air pollution, water pollution, etc.), reduce the use of natural resources and be recycled and reused. It should reduce the capital and operation cost of machinery and equipment and reduce energy consumption (Hydes & Creech, 2000).

3.3.11. Environmental protection requirements
Environmental protection needs come from human life, social development and natural ecology. In this study, environmental demand is identified as flow, and environmental awareness is identified as stock. The higher the environmental demand, the stronger the environmental awareness.

3.3.12. Green resources
Green resources mainly refer to renewable resources (biological, water, land resources, etc.) and inexhaustible resources (such as wind, solar energy, etc.). Green resources can be reproduced in a relatively short period of time, or will not lead to a reduction in storage after being used.

3.3.13. Environmental regulations
Environmental regulations are regulations for producers and operators discharging pollutants to prevent the generation of waste gases, wastewater and residues in production, construction or other activities. The greater the number of environmental regulations, the fewer the number and types of pollutants. Environmental regulations encourage manufacturing to reduce the use of contaminated equipment (Kibira et al., 2009).

3.3.14. Environmental awareness
Environmental awareness is the level and degree of people’s understanding of the environment and environmental protection. It is also the consciousness of people to constantly adjust their own economic activities and social behavior to protect the environment and coordinate the practical activities of people and the environment as well as people and nature. In this study, environmental awareness is taken as a horizontal variable. With the improvement of environmental design, environmental awareness is gradually enhanced.

3.3.15. Environmental impact
Manufacturers, as environmental entities, have a great impact on the environment (Kibira et al., 2009), including both positive and negative impacts on the environment. In this study, this mainly refers to the degree of environmental benefits and the reduction of adverse impacts.
Environmental agreement: In the case of environmental agreements, manufacturing pollution and emissions can be limited, and the percentage of recyclable materials and recyclable products used by manufacturing enterprises in manufacturing products can be limited.

3.3.16. Corporate profits
The ability of manufacturing to generate profits, including the continuity of enterprise development, and its contribution and impact on society (Kibira et al., 2009).

3.3.17. Health requirements
The environment is associated with human health and has an impact on health (Sandifer, Sutton-Grier, & Ward, 2015). As a result, health needs for the environment are generated, and health needs should be taken into account in design and manufacture.

3.3.18. Natural resources
The goal of natural resource sustainability is to protect, proliferate (renewable resources) and rationally utilize natural resources in order to improve the ability of resource regeneration and sustainable utilization and to achieve the unification of environmental benefits and social and economic benefits.

3.3.19. Policy
The policy factors in this study are a series of requirements and guidelines. Flexible policies are conducive to the sustainable development of green manufacturing and enhance environmental regulations and environmental agreements.

3.3.20. Social impact
Social impacts of sustainability include social equity, social services, gender equality, social responsibility and participation (Harris, 2003).

3.3.21. Economic impact
Economic impact mainly refers to the sustainable economic system, economic chain and economic growth. Sustainable economic development has achieved success. Economic and social issues are embedded in environmental issues (Montabon, Pagell, & Wu, 2016).

3.4. Building a logical model
When constructing a logical model between variables, there is no need for a proportional influence relationship between variables; that is, a qualitative model of system dynamics is established by logical causality between variables, as shown in Figure 2.

Through expert interviews, DC (design concept) and MT (manufacturing Technology) are shown to be the main variables affecting design and manufacturing sustainability. Combined with Figure 2, the logic of how DC and MT affect SD (sustainable development) is explained: DC affects SD indirectly through the rate variable EFD (environmentally friendly design), horizontal variable MC (manufacturing cost) and the auxiliary variable CP (corporate profits); MT affects SD indirectly through the auxiliary variable IA (innovative approach), rate variable GR (green resources), horizontal variable natural resources (NR) and the auxiliary variable EI (environmental impact).

To more clearly explain the logic of how DC and MT affect SD, the Vensim software was used to draw the Causes Tree diagram with clearer logical relationships. The colors of the variables are consistent with Figure 2 (SD qualitative model), as shown in Figure 3; the specific quantification impact will be further analyzed in 4.1 and 4.2.

3.5. Data and equation
Data from the case study framework were collected through semi-structured interviews (Hama Kareem, Mohamad Al Askari, & Muhammad, 2017). As a semi-structured interview method, a focus group was used in this study. This was determined by expert discussion of the focus group method.
Through expert discussion, it was shown that (1) the relationship between variables was determined to be positively affected. As shown in Figure 2, for example, the impact symbol of the variable EFD points to the variable EFD being “+”—that is, as the value of a variable increases, the value of another variable will also increase; and (2) the proportion of influence between variables was determined. Since the determination of some values involved cross-departmental expert discussion, and it was necessary to combine manufacturing, it took a long time. After determining the specific influence relationship ratio, the experts replied by email, and all the feedback was organized.

Through the logical relationship of variables and data, the modeling equation was obtained. There are three main types of equations in this study. The first is constant—the constant of PP is 200, and the constant of DC, MT, MC, HR, and PF is 100. The second is the equation of horizontal variables, including (1) and (2). The determination of the third equation is illustrated by an example in Figure 3: EI is affected by both EPR and NR. After discussion by experts, it was determined that the value of EPR’s influence on EI is 5, and that of NR’s influence on EI is 0.4. Then, the function formula of EI is $EI = 5EI + 0.4NR$, and the equation of auxiliary variable is (3)—(17).

1. $NR = \text{INTEG}(GR, 10)$
2. $EAW = \text{INTEG}(EFD, 60)$
$SD = ECI \cdot 0.5 + EI \cdot 0.4 + SI \cdot 0.6$
$DS = ER \cdot 0.3$
$EFD = DC \cdot 10 + MC \cdot 0.4 + EA \cdot 0.4 + DS \cdot 0.4 + DR \cdot 0.8 + EAW \cdot 0.2$
$DR = EPR \cdot 0.6 + HR \cdot 0.4$
$IA = MT \cdot 10$
$PC = GE \cdot 5$
$GE = EA \cdot 0.5 + ER \cdot 0.5$
$EPR = CP \cdot 0.3$
$GR = (IA \cdot 0.4 + PC \cdot 0.3 + PP \cdot 0.1 + NR \cdot 0.2) \cdot 3$
$ER = PF \cdot 50$
$EI = GE \cdot 0.3 + NR \cdot 0.4 + EPR \cdot 5 + EAW \cdot 4$
$EA = PF \cdot 50$
$CP = IA \cdot 0.6 + EAW \cdot 0.4$
$SI = EPR \cdot 0.6 + HR \cdot 0.4$
$ECI = CP \cdot 0.3$

3.6. Data implantation
The data of expert interviews and discussions was analyzed through the computer software for system dynamics, Vensim, with its simulation technology as an auxiliary means. The time range was determined to be 2015–2025, the time step was determined to be one year and the DC and MT weights were determined to be 100, 300, and 1000. The relevant values and influence ratios were input into the corresponding variables, the information feedback mechanism and the causal cycle principle were used to simulate the sustainable development trend of design and manufacture, and the quantitative and qualitative system dynamics model was constructed.

4. Results and discussion
Chapter 3.3.2 shows that DC and MT were identified as the main variables; thus, we focus on the impact of DC and MT on sustainable development (SD) from 2015 to 2025.

4.1. The impact of design concepts on sustainability
Figure 4 shows that the X-axis is the time axis, and the starting time is 2015, resulting in a time-span of 10 years by 2025. The bigger the Y-axis, the bigger the impact will be. The weights of DC-100, DC-300 and DC-1000 are 100, 300 and 1000, respectively.

As can be seen from the graph, by setting three different weights, the three curves formed grow over time, and the influence of DC on sustainable development (SD) is positive. By changing the weight of DC, the changes in sustainable development can be affected, as shown in Table 2.

From the data of 2016 to 2025, it can be seen that the sustainable impact of the design concept on design and manufacturing shows an increasing trend and achieves a dynamic balance of growth. From the data over 10 years, it can be predicted that the sustainable impact of design concept on design and manufacturing will have a long-term positive impact. In the future, we should continue to pay attention to the importance of the sustainable impact of design concept.

The design concept of environmental awareness aims at transforming global social and environmental problems and determines the level of sustainable utilization of environmental resources. Designers’ social responsibility and environmental awareness are key factors for sustainability and have an important impact on sustainability (Deniz, 2016). Design concepts provide a creative approach to problem solving and help solve pressing sustainability issues (Shapira et al., 2017). The use of sustainable and
socially responsible design in industry can reduce energy consumption and environmental impacts. Design-oriented sustainability can effectively enhance the competitiveness of manufacturing-related industries and promote industrial success (Aversa, Petrescu, Petrescu, & Apicella, 2016).

### 4.2. Impact of manufacturing technology on sustainability

Figure 5 shows that the X-axis is the time axis, and the starting time is 2015, which results in a time-span of 10 years by 2025. The bigger the Y-axis, the bigger the impact will be. The weights of MT-100, MT-300 and MT-1000 are 100, 300 and 1000, respectively.

![Figure 5. Curve graph of the impact of manufacturing technology on sustainability.](image)

### Table 2. Data sheet of the impact of design concepts on sustainability

| Time | 2016  | 2017  | 2018  | 2019  | 2020  |
|------|-------|-------|-------|-------|-------|
| DC-100 | 11,956 | 27,003 | 47,957 | 77,558 | 119,982 |
| DC-300 | 15,842 | 35,777 | 62,878 | 100,208 | 152,354 |
| DC-1000 | 29,444 | 66,486 | 115,099 | 179,485 | 265,655 |

| Time | 2021  | 2022  | 2023  | 2024  | 2025  |
|------|-------|-------|-------|-------|-------|
| DC-100 | 181,653 | 272,517 | 408,081 | 612,633 | 924,387 |
| DC-300 | 226,250 | 332,489 | 487,387 | 716,255 | 1,058,590 |
| DC-1000 | 382,339 | 542,389 | 764,960 | 1,078,930 | 1,528,290 |

Figure 4. Curve graph of the impact of design concepts on sustainability.
As can be seen from the graph, by setting three different weights, the three curves formed grow over time, and the influence of MT on sustainable development is positive. By changing the weight of MT, it will affect a change in sustainable development, as shown in Table 3.

From the data from 2016 to 2025, it can be seen that the sustainable impact of manufacturing technology on design and manufacturing is increasing, achieving a dynamic balance of growth. From the data over 10 years, it can be predicted that the sustainable impact of manufacturing technology on design and manufacturing will be positive in the long term. In the future, we should continue to pay attention to the importance of the sustainable impact of manufacturing technology.

Technological innovation is an effective means to optimize important resources in social and economic systems. Some theoretical viewpoints will limit the potential of technological innovation. It is necessary to systematically analyze and manage technological innovation for sustainable growth from a holistic perspective (Cancino, La Paz, Ramaprasad, & Syn, 2018). We incorporated manufacturing technology into the design and manufacturing system to simulate the impact on sustainable development. It was proven that technology is an important measure for the sustainable development of the manufacturing industry and is of great significance for achieving the sustainable development of the manufacturing industry. Sustainable manufacturing concepts are linked to the latest technologies, such as the implementation of new technologies such as energy conservation, which have provided significant results in supporting sustainable manufacturing (Kishawy et al., 2018). The application of technologies can effectively promote sustainable development (Singla, Ahuja, & Sethi, 2018).

4.3. Contrastive analysis
We uniformly select the value weighted as 1000 to further compare and analyze the impact of design concepts and manufacturing technology on sustainable development, as shown in Figure 6. As can be seen from Figure 6, when the weights of MT and DC are 1000, the red line is higher than the blue line, indicating that DC has a more significant impact on sustainable development than MT. For example, new manufacturing technologies with energy savings can make energy-saving systems that affect the environment more energy efficiently. However, in order for these technologies to have an effective impact on the realization of sustainable systems, they need a huge amount of capital investment (Kishawy et al., 2018), while the design concept does not have a high cost. As the population increases, the manufacturing industry must focus on global development and competition, and the principles of lean manufacturing must be implemented and continuously improved. In this context, the demand for technology is stronger than ever before, resulting in the steady increase of the productivity of existing product models and even the development of new product models (Ali Naqvi, Fahad, Atir, Zubair, & Shehzad, 2016). However, design concepts play a crucial role in the early stages of product development, affecting the development process and the success of the products developed (Zhai et al., 2009). Design concepts incorporate sustainability into the early stages of manufacturing (Wisthoff, Ferrero, Huynh, & DuPont, 2016) and

| Time  | 2016  | 2017  | 2018  | 2019  | 2020  |
|-------|-------|-------|-------|-------|-------|
| MT-100| 11,421| 25,506| 45,302| 73,531| 114,364|
| MT-300| 13,171| 28,292| 49,602| 80,072| 124,261|
| MT-1000| 19,294| 38,043| 64,653| 102,965| 158,902|
| Time  | 2021  | 2022  | 2023  | 2024  | 2025  |
| MT-100| 174,249| 263,212| 396,936| 600,058| 911,425|
| MT-300| 189,229| 285,963| 431,666| 653,381| 993,778|
| MT-1000| 241,659| 365,592| 553,219| 840,012| 1,282,010|

Table 3. Data sheets of the impact of manufacturing technology on sustainability
determine the direction of sustainable development. It can be seen from the two curves in Figure 6 that the effect of design concepts is more significant than that of manufacturing technology. When considering the sustainable development of design and manufacturing, priority should be given to the importance of design concepts.

5. Conclusion
Sustainable development is dynamic, comprehensive, and complex. Variables are interrelated and interact with each other. This paper is a pilot study to apply system dynamics to the relationship between design and manufacturing. It demonstrated the superiority of system dynamics in the analysis of design and manufacturing for sustainability issues. In the application of the system dynamics method, this study combined focus group interviews to determine the relationship between variables and a quantitative relationship to solve the measurement of soft variables and to provide ideas for sustainable development assessment methods.

Through the application analysis of system dynamics on the sustainable impact of design and manufacturing, two key variables (design concept and manufacturing technology) determined by experts were analyzed, and it is shown that the impact of the design concept and manufacturing technology on sustainable development is positive.

In addition, the impact of design concepts on sustainability is more significant than manufacturing technology. Therefore, in the manufacturing process, enterprises should pay attention to the innovation of design concepts while improving manufacturing technology and gradually adjust the design concepts to meet the sustainable requirements of changing times. At the same time, we encourage as many designers as possible to participate in sustainable development (Shapira et al., 2017) to promote the sustainable development of design and manufacturing. The results of this paper provide the basis and a decision-making reference for the sustainable development of design and manufacturing and will contribute to arouse the environmental protection consciousness of design and promoting the sustainable development of the manufacturing industry. Most importantly, it provides manufacturing managers and designers with a way to systematically think about solving sustainable manufacturing problems as a whole.

It should be noted that the sustainable research of design and manufacturing involves the interrelationship of unmeasurable soft variables. This paper presents a proposal for the research method of system dynamics for sustainable design and manufacturing to promote the discussion of this critical topic, collect feedback on its improvement, and encourage readers to provide feedback to the authors to support the further development of the study. This study involves limitations. The data collected

Figure 6. Curve of the impact of design concepts and manufacturing technologies on sustainability.

SD : DC \ -1000
SD : MT \ -1000
through focus groups may not be very accurate. In the future, data from manufacturing practice should be obtained to improve the model and tested in cases to improve the accuracy of the simulation and prediction of the model.

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