# A Framework for Co-Designing Product and Production System to Support Resource Efficient Manufacturing

by

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*"Real knowledge is to know the extent of one's ignorance."*

*- Confucius -*

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# SYNOPSIS

This thesis reports on research undertaken to investigate how to advance the current practices of resource efficiency and sustainability consideration in manufacturing business through the simultaneous design of Product and Production System (P&PS). The primary objective of this research is the development of a framework and methods to support a manufacturer to transform the current independent design processes into a single design process facilitating designs of resource-efficient P&PS.

The research contributed in this thesis is structured into three major parts. The first part reports the literature reviewed to define and refine the key objectives of this research. In this review part, the basic knowledge and current practices of Product Design (PD), Production System Design (PSD), Integrated Design (ID) and Sustainable Design (SD) are explored in order to understand the shortcoming of ID and SD. It has been discovered that current ID practice was to facilitate information exchange between the design process. In which majority of the integrated consideration was conducted to succeed the conventional design targets (i.e. reducing design cost, shortening development time and improving manufacturability of design) than the contemporary targets such as increasing resource efficiency through sustainability consideration. While the current practices of SD often return only an incremental benefit because of the inabilities to access information and to assess sustainable decisions between PD and PSD processes. Moreover, the current practice of ID through information exchange is not sufficient to initiate these abilities which can be performed via a collaborative design process. Thus, there is a need to shift a current integrated practice between individual design processes into a single combined process for designing resource-efficient P&PS at once.

In response, the second part of this research introduces a framework for co-designing product and production system, which assist companies in transforming their current independent design process into a single process for designing resource-efficient products and production systems simultaneously. The framework offers methods to study the feasibility of collaborative design adoption and to specify the potentially collaborative decisions within PD and PSD processes. Based on the identified decisions, the optional strategies are recommended to create a customised P&PS design process for the companies with the different design needs.

Lastly, the third part of the thesis describes the case studies conducted to demonstrate the implementation and refine the applicability of this framework. These are demonstrated through a simple product designed by an in-house designer and a complex product designed by internal and external designers. The results were used to improve the framework and methods for the wide-ranging implementation.

In summary, this research reported in this thesis has concluded that the present ID practice via individual design processes is insufficient to deal with the recent requirement of sustainability. This highlights the importance of enabling a collaborative process for designing and assessing both P&PS together in order to improve environmental benefit. A systematic framework to visualise the benefit of collaborative design, to identify the collaborative consideration and to create a single design process provides to offer opportunities to create P&PS with more efficient use of resources.

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# ABBREVIATIONS

| | |
|---|---|
| AE | Auxiliary Energy |
| C | Consumed water |
| CAD | Computer-Aided Design |
| CAM | Computer-Aided Manufacture |
| CAPP | Computer-Aided Process Planning |
| CE | Concurrent Engineering |
| CPD | Collaborative Product Development |
| DE | Direct Energy |
| DfA | Design for Assembly |
| DfM | Design for Manufacturing |
| DNR | Discharged Non-Renewable water |
| DRW | Discharged Renewable Water |
| DSM | Design Structure Matrix |
| EMI | Early Manufacturing Involvement |
| EMS | Environmental Management System |
| EPE | Embodied Product Energy |
| FPD | Frequency of Product Design |
| FPSD | Frequency of Production System Design |
| GPDP | Generic Product Development Process |
| ID | Integrated Design |
| IDEF | Integrated computer-aided manufacturing DEFinition |
| IDPPP | Integrated Development Process of Products and Production systems |
| IE | Indirect Energy |
| IM | Information Modelling or language tools |
| $IP^2D^2$ | Integrate Product and Process Design and Development |
| IPD | Integrated Product Development |
| IPPD | Integrated Product-Process Development |
| MFAM | Material Flow Assessment |
| NPW | Non-Production Water |
| P&PS | Products and Production Systems |

| | |
|---|---|
| PD | Product Design |
| PDM | Product Data Management systems |
| PDMA | Product Development and Management Association |
| PDU | Product Design Update rate |
| PDW | Production Water |
| PPC | Product and Production system Co-design software tool |
| PSD | Production System Design |
| PW | Process Water |
| QFD | Quality Function Deployment |
| REM | Resource-Efficient Manufacturing |
| SD | Sustainable Design or design for sustainability |
| SE | Simultaneous Engineering |
| STEP | STandard for the Exchange of Product model data |
| SW | System Water |
| TE | Theoretical Energy |
| WER | Water usage Efficiency Ratios |
| WI | Water Intensity |
| WWE | Waste Water Efficiency |

# TERMINOLOGY

**P&PS Co-design / Co-design of P&PS**

In this thesis, the term ‘P&PS Co-design’ is defined as ‘a single combined process to simultaneously design the product and production system required to manufacture them’. This term denotes to a future for current integrated design concept when designs of product and production system are equally, simultaneously and collaboratively considered by both product and production system designer with the interest of attaining the maximum environmental benefits. The detailed description is also provided on Page 3 and 81.

**Production system change**

Production system change in this thesis refers to a change within the production system which can be a process flow/layout change, a production process changes and/or a machine tool change. The detailed explanation is provided in section 8.2.3 (see Page 93).

**Environmental/Ecological aspect**

This work intended to develop a framework for supporting and improving the collaboration between product and production system design in terms of information exchange and interaction for improving environmental/ecological consideration. However, based on the limited study time and the complexity of the developed steps within the framework, resource efficiency was selected and applied as the environmental/ecological constraints in this thesis.

**Resource efficiency**

Resource efficiency means *“using the Earth's limited resources in a sustainable manner while minimising impacts on the environment. It allows us to create more with less and to deliver greater value with less input”* (Commission 2011)

Resource-Efficient Manufacturing (REM) is currently recognised as manufacturing that aims to conserve available resources and minimise environmental impact in order to sustain the future of manufacturing (Gould and Colwill 2015).

Regarding the timeframe and limited data, the resource efficiency in this thesis includes a consideration of energy, material and water efficiency (e.g. material elimination, material minimisation, material substitution, material separation, energy minimisation, energy source substitution, water minimisation and wastewater treatment) which are the most relevant resource used within many manufacturers.

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# CHAPTER 1 INTRODUCTION

Manufacturing businesses are currently facing market challenges from changeable customer demands, frequent product updates, and shorter service life of products (Huisman *et al.* 2012, Xiong *et al.* 2016). At the same time, the rapid growth of consumption has contributed to an environmental crisis, involving resource scarcity, global warming, and rapid climate change, which has been unfolding over the past decade. These challenges will become more critical because the world population is expected to reach approximately 9,000,000,000 peoples by 2050 (WWAP, 2015). Under these circumstances, manufacturing businesses should be flexible and instantly responsive to challenges such as these to maintain their competitiveness.

To become more responsive, for more than two decades manufacturers have attempted to reduce time to market through the improvement of product design and development processes. The process of production system development, which conventionally starts after product design, is now often carried out concurrently with the product design process. In an academic context, this approach is often referred to as Integrated Design concept (ID), Integrated Product Development (IPD), Simultaneous Engineering (SE), or Concurrent Engineering (CE) (Tomiyama *et al.*, 2009). This concept is realised by early and uni-directional information sharing between Product and Production System (P&PS) design teams using advanced information technology and information exchange through STEP (STandard for the Exchange of Product model data) (Pratt 2001). However, through such integrated approaches, product design and production system design still operate independently. Besides, design collaboration can occasionally form late, when an unexpected problem such as a quality issue is detected and then solved in a limited or provisional fashion. This current practice of integration needs to be enhanced to enable flexible responses and ways to handle immediate and unavoidable challenges such as resource efficiency.

In current practice, sustainable manufacturing entails the attempt to reduce resource consumption and environmental impacts by using various resource-efficient methods. Most of these reactive methods principally improve or replace the installed production facilities during the production phase, at which point any changes to product design are limited. This is because all the design ideas and decisions have already been approved, realised and transformed into the physical objects. In fact, design changes (redesign) are not preferable, since they require increased investment in resources and time. Consequently, these "sustainable" adaptations have generally resulted in only incremental benefits. To achieve the radical improvement, sustainability should be considered further upstream, at an early stage of the design process. This is where flexibility in designing P&PS is still highly feasible through a proactive approach (Sheldrick and Rahimifard 2013).

To successfully apply sustainability early on in the design process, there is a need to instantly understand the impact of a decision on one design process on the other one. For example, during a conceptual design stage, a designer should be able to consider alternative materials and select the material that has the lowest environmental impact. To make an environment-friendly decision on this material issue, product designers need to assess the impact of alternative materials on a design of the production system. Based on product design background, knowledge and experience, production system designers are required to support this sustainable assessment between P&PS.

In this context, the current practice of integrated design (through information sharing) between individual design manners is not sufficient to support environment-friendly decisions because such practice could not ensure that all required information to support sustainability considerations is shared and/or understood by the user from various background. Similarly, the design of the production system should be considered in concert with a sustainable product design approach (Ali and Gupta 2010, Ranky 2010, Haapala *et al.* 2013). These challenges highlight a clear need to extend the scope of the current integrated design by combining the two into a single collaborative design process that simultaneously considers the product and production system design decisions and their impact on each other, a concept referred to as co-design of P&PS in this thesis (see Figure 1.1).

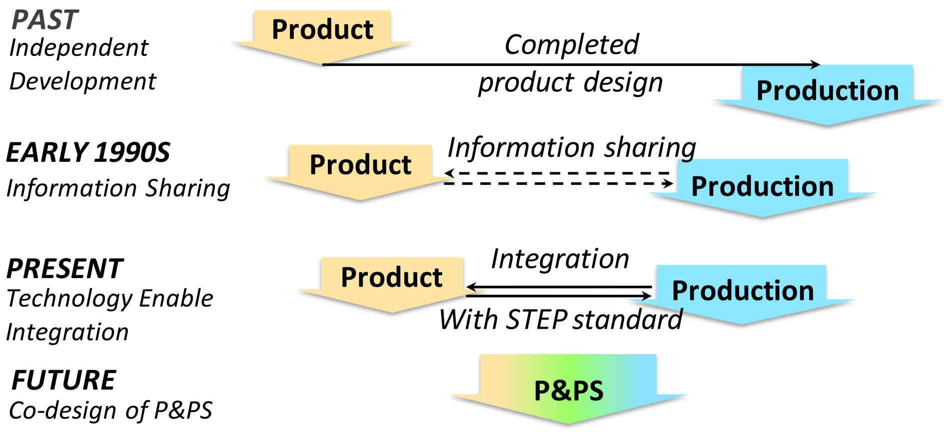

*Figure 1.1 - The proposed evolution of integrated design toward Co-design of P&PS*

However, this single collaborative and combined design process is not expected to be suitable for all manufacturers. Instead, such a process will provide more potential benefits to a manufacturing business which frequently updates the design of their products, in particular, if changing the design of the product requires a change of process flow, production process and/or tooling in the production system. For instance, the selection of different primary and secondary material during every new packaging design leads to the requirement of different production processes.

The research reported in this thesis aims to create a framework to combine design processes of product and production system in order to provide the ability to visualise the interaction between the design of the product and its production systems to maximise the potential for resource efficiency. This is achieved through:

1. Identification of key challenges and future drivers for the integration of product and production system design.
2. Identification of the current state of integration between the design processes of P&PS and the level of integration needed to support sustainability.
3. Development of a framework that offers manufacturers support in integrating their currently separate design processes into a single **co-design** process of product and production systems to enhance resource efficiency.

It should be noted that the term ‘co-design’ is used as a participatory design process where problems, ideas, and decisions are reflected on by the designer and by other non-designers, such as researchers, developers, and especially customers and consumers, in order to better clarify product or service requirements (Taffe 2015).

Nonetheless, in this thesis the term ‘co-design’ implying a future for conventional integrated design when designers can collaboratively design product and production system simultaneously in the interest of attaining the more benefits of the resource-efficient application.

This thesis comprises three main sections, namely the research background and overview, theoretical research and model development, and research conclusions. The structure of the thesis is illustrated in Figure 1.2.

The first section (research background and overview) contains the first six chapters. Following this introduction, Chapter 2 presents the research justification, research questions, research aim and objectives, and research scope. Then, basic knowledge and current practices of product design,

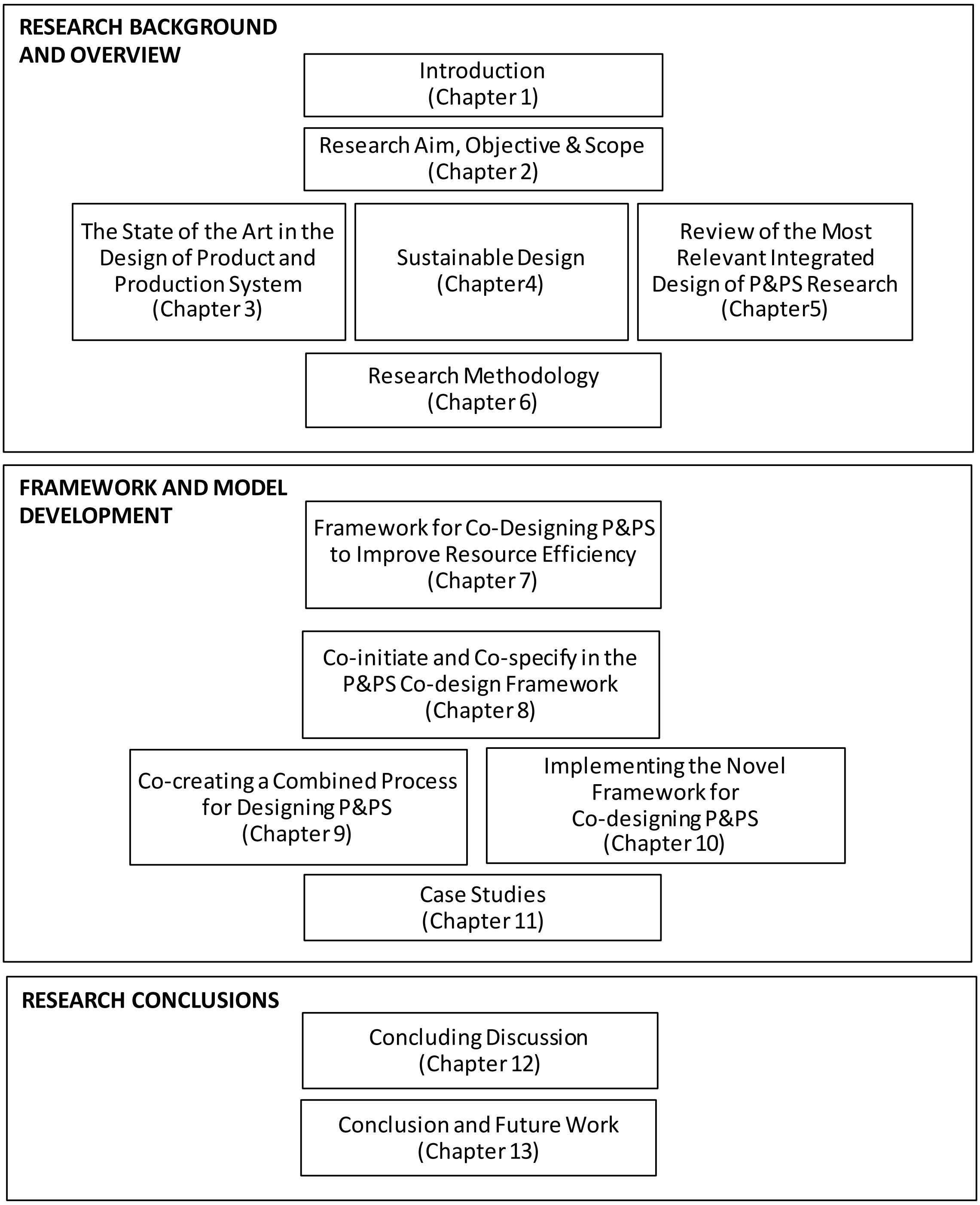

*Figure 1.2 – The structure of the thesis*

production system design and the concept of integrated design are introduced in Chapter 3. Chapter 4 investigates the present challenge like sustainability, which requires to be supported by the integrated design of P&PS. Chapter 5 provides a detailed review of the most relevant research in the integrated design of P&PS. It also presents an investigation into the current integration between these design processes through interrelation and interaction. The overview of the literature included in Chapter 3 -5 is presented in Figure 1.3. Chapter 6 describes the methodology adopted to undertake this research.

The theoretical research and framework development section consists of five chapters, which detail the proposed framework, including its four main phases and implementation toolkit, and present case studies for demonstrating framework applications. This section starts with Chapter 7, which introduces a framework for co-designing product and production systems to support resource-efficient manufacturing, itself comprised of four main phases, namely Co-initiate, Co-specify, Co-create, and Co-implement. Chapter 8 provides detailed steps in the first two phases of the framework, which provides support for a manufacturing business to help identify the feasibility and benefits of co-design adoption and specify where the potential co-design decisions are in current design processes. Subsequently, Chapter 9 documents the third Co-create phase, which offers three optional approaches for creating a co-design process with different applications based on the specified co-design decisions in the second phase. Chapter 10 explains how the three previous phases of the framework can be implemented through a co-design toolkit consisting of applicable software tools and the proposed P&PS Co-design prototype software tool. Chapter 11 demonstrates the application of the proposed framework with two case studies. The final section of research conclusions contains two chapters. Chapter 12 discusses the findings and implications of this research in relation to the original key research objectives. Finally, Chapter 13 presents the final research conclusions and suggests directions for future work.

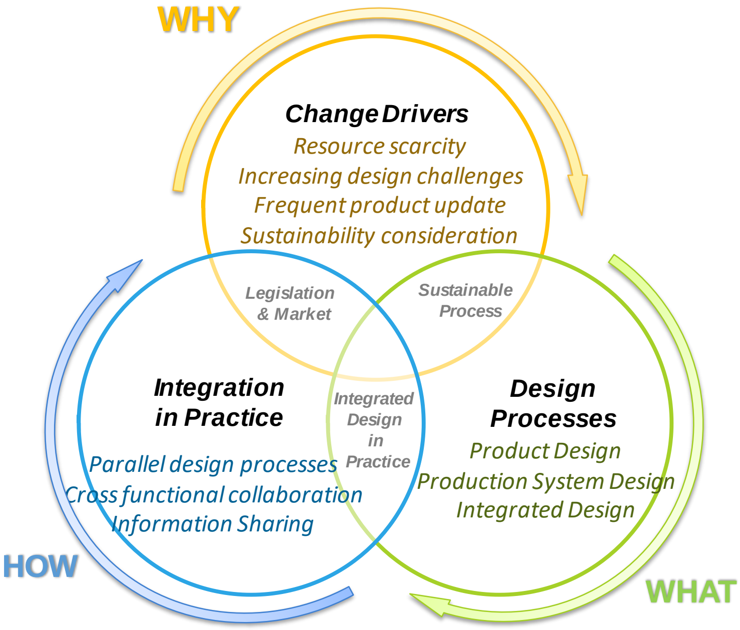

*Figure 1.3 – Main areas of literature review*

# CHAPTER 2 RESEARCH AIM, OBJECTIVES AND SCOPE

## 2.1 INTRODUCTION

This chapter presents the research aim, objectives and scope of this thesis. The chapter begins with the research justification and hypothesis as detailed in the next section. Then, the questions, aim, objectives and scope of this research are defined in the following sections.

## 2.2 RESEARCH JUSTIFICATION AND CONTEXT

The design and development department is of central importance in all manufacturing businesses because decisions made by designers have a bearing on almost every aspect of a product or a production system (Pahl *et al.* 2007). Accordingly, the designer often works under high pressure subject to key design challenges such as regulation, cost factor and consumer preferences. In addition, reduction of development time is a common goal because of its status as a crucial factor leading to company success. As depicted in Figure 2.1, the Product Development and Management Association (PDMA) survey reported that the product development best practices (88 of 453 firms all over the world which have a high success rate in NPD) commonly involve the first-to-market strategy as a key to maximising design achievement (Markham and Lee 2013).

As mentioned in the introduction, concepts of integrated design have frequently been proposed and implemented to speed up design and development. In a research context, most studies in

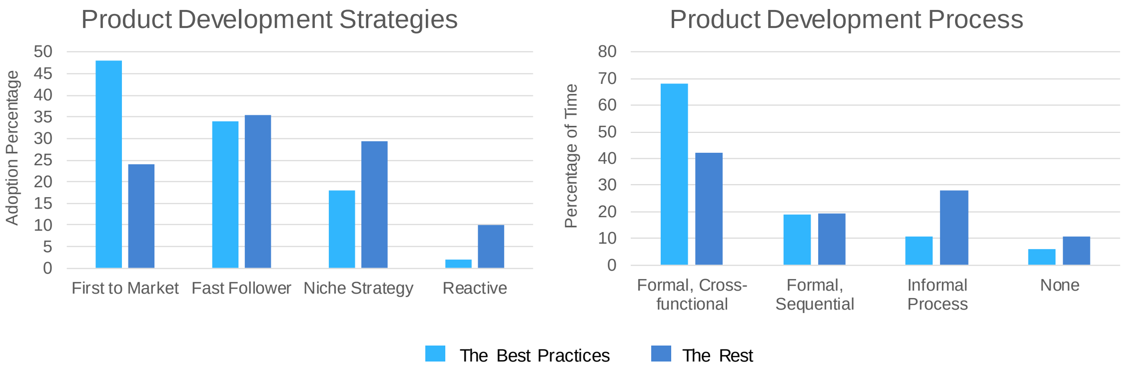

*Figure 2.1 – New product strategy and product development process (Markham and Lee 2013)*

the field of integrated design has only focused on improving one of its four key characteristics. These characteristics are i) encouraging parallel activity, ii) considering critical issues early in design, iii) exchanging information, and iv) maintaining collaboration between teams. As a foundation of the integrated design concept, the first ‘encouraging parallel activities’ and the second ‘considering critical issues’ areas were originally developed in the literature almost three decades ago to describe and provide a basic approach or guideline for implementing the integrated design. Based on technological advancement, current research focuses more on developing the technology or software tools (i.e. information sharing, knowledge management, and design simulation tools) to support the third characteristic, information exchange. Likewise, much current academic attention has been paid to the improvement of design collaboration instead of developing a new integrated design process. Apart from reducing development time, several integrated design studies also recommended other goals such as improving product quality, design cost, productivity, and flexibility (Rupak *et al.* 2008, Brown *et al.* 2012, Jeang and Lin 2014, Gopalakrishnan *et al.* 2015).

A common observation is that most of these applications were mainly utilised to meet a narrow target such as cost and time reduction, rather than satisfying all integrated requirements (Winner *et al.* 1988, Gerwin and Barrowman 2002). More importantly, the present challenges in designing products and production systems are becoming increasingly complex due to more changeable customer demands, frequent product updates, and requirements for resource efficiency. To tackle these rising complexities in P&PS development, Gräßler and Yang (2016) have highlighted that *“traditional discipline-specific development methods reach their limits because of missing interdisciplinary collaboration.”* Hence, the current application of an integrated design concept which can accommodate integration among separate design processes should be enhanced to facilitate the single collaborative process.

Similarly, the need for an approach involving the integration between product and production system has also been raised by various studies in the sustainability area. For example, Haapala et al. (2013) mentioned that the need for environmental manufacturing processes could be initiated and managed from product design specification; thus, manufacturing must be defined in concert with the product design process. Likewise, Ramani et al. (2010) have underlined that collaboration between design and manufacturing is essential to cope with the increasing challenge of sustainable development.

In a sustainable design context, Sheldrick and Rahimifard (2013) have stated that *"to maximise the potential of sustainable design, there is a need of further investigation of the linking of SD practices with other relevant activities within a manufacturing company, such as process and plant design"*.

The requirement of considering product and production system design in a concurrent fashion has been put forward for the reason that the current sustainability practices still cannot provide a radical breakthrough. Current studies of sustainability or resource efficiency in manufacturing have tended to focus on identifying and improving resource-inefficient production facilities rather than on providing the ability to select improved or newly-emerging processes during product design and process planning. This therefore indicates a need for further research based on a proactive approach (Ramani *et al.* 2010). Consequently, many academic studies have proposed proactive methods to design sustainable products. Although these have been progressively developed, they have largely failed to be successfully adopted and implemented in practice (Short *et al.* 2012). One of the key reasons is that a lack of understanding, concerning the impact on the resource efficiency of manufacturing processes (Costa *et al.* 2015, Dekoninck *et al.* 2016). Designers can easily select a familiar solution that might not be environmentally friendly because of the inability to visualise the effect of changes between the P&PS.

For these reasons, integrated design currently needs to be able to satisfy not only conventional challenges such as development time but also critical challenges like sustainability, especially its environmental aspect. In response to this, to attain the more benefit of sustainable design, several studies have recently sought to apply integrated consideration of product and production systems. Examples include studies concerning an ecological policy for chemical product development and production planning (Choy *et al.* 2016), the Enterprise Sustainability Index for products and processes evaluation (Huang and Badurdeen 2017), and incorporation of resource consumption of production processes and LCA into product design (Lacasa *et al.* 2016).

This research therefore extends the scope of previous ID research by focusing on the co-design process of product and production system for supporting resource-efficient manufacturing. Through an examination of current integrated design concepts, this research seeks to determine ways to combine P&PS design processes through right information at the right time. As such, the scope of the research reported in this thesis focuses on the product design, production system design and production operation phases, as depicted in Figure 2.2.

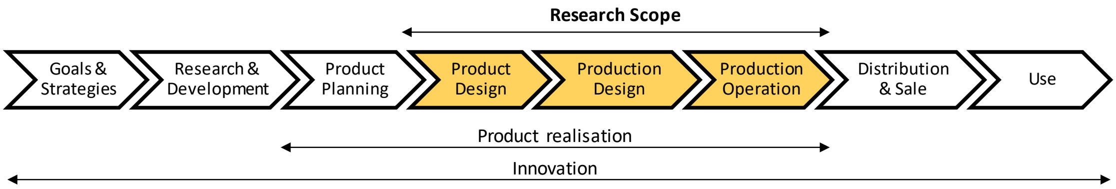

*Figure 2.2 – The product realisation process: part of the innovation process (adapted from Säfsten and Johansson 2005)*

It is hypothesised that a systematic P&PS Co-design framework will support manufacturers to consider designs of product and production system equally through a new combined design approach based on the consideration of resource efficiency.

## 2.3 RESEARCH QUESTION

In this research, the main research question is as follows: “How can we support manufacturing to move forward from their current separated design processes into a single co-design process of product and production system in order to enhance resource efficiency?” In addition, the following questions can provide a more detailed overview of research challenges.

- What are the existing drivers, barriers, methods, and practices of the integrated design and environmental design of products and production systems?
- Which design decisions regarding the product and production system need to be collaboratively considered to promote resource efficiency effectively?
    - At what stages do these design processes need to be linked to promote resource efficiency effectively?
    - What information needs to be shared between product design and production system design?
- How can we best facilitate collaborative decision-making in a framework that combines the design of product and production system into a single process?

## 2.4 RESEARCH AIM AND OBJECTIVES

This research aims to investigate the current integration between the design processes of product and production system and to develop a framework for combining these processes in order to maximise the potential for resource efficiency. To meet this aim, the following objectives have been identified:

1. To review the state-of-the-art and current practices (including the sustainability and resource efficiency consideration) of product design, production system design, and integrated design processes.
2. To examine the ways ID are interrelated and interacted and review the most relevant research in integrating design processes of product and production system.
3. To produce a framework for supporting manufacturers to combine their current independent design processes into a single co-design process for both the product and production system to improve their resource efficiency.
4. To develop a toolkit supporting the implementation of the proposed framework for co-designing product and production system.
5. To demonstrate and refine the applicability of the framework through case studies and refine the framework based on case studies finding.

## 2.5 RESEARCH SCOPE

In line with the objectives, the scope of this research is defined in the following sub-sections.

### *2.5.1 Review the state-of-art and the current practices of product design, production system design, and integrated design*

Chapter 3 and 4 will review the literature to achieve Research Objective 1. Chapter 3 entails a detailed review of approaches and methods for designing product and production system as well as examining the basic knowledge and concepts related to integrated design processes of product and production system. This also identifies the critical issue of current practices in these design areas. In Chapter 4, the state-of-the-art review of the sustainable design, especially, a consideration of resource efficiency, will be further investigated to identify its current practices during the manufacturing phase. The findings from these two chapters will then be utilised to address the Research Objective 2.

### *2.5.2 Review the most relevant research in integrated design and examine the current state of the integration between design processes and their interrelation and interaction*

To address Research Objective 2, Chapters 5 will examine the current state of integration between product and production system design teams. This is to model the information flow between design processes of products and production systems and to investigate how various design teams integrate based on aspects of interrelation (information requirement and exchange) and interaction (collaboration). Moreover, based on these two aspects of integration and key characteristics of ID, the review of the most relevant research regarding integrated consideration of product and its production system and environmental consideration will be provided. Then, the future requirements for design processes from both conventional and resource efficiency viewpoints will be identified based on the findings of the reviewed literature.

### *2.5.3 Produce a framework for co-designing product and production system to support resource-efficient manufacturing*

Chapters 7, 8 and 9 will address Research Objective 3. The mixed approaches and information from the investigation phase will be utilised and applied to develop a framework for improving the resource efficiency of production system through equal and collaborative consideration of product and production system within a single design process. This will be developed to support the current manufacturing businesses which have different products, production systems and design practices (e.g. product type, resource use in a production system, design process, design control and organisational size). Hence, this will help manufacturers and designers to clarify their benefit from adopting a new process. A set of design methods will be generated to assess the existing design processes and to transform and apply a new design process which improves design consideration, interaction and integration in order to improve resource efficiency.

### *2.5.4 Develop a toolkit supporting the implementation of the proposed framework*

In Chapter 10, the proposed P&PS Co-design framework will be further refined. In parallel, a toolkit supporting the implementation of P&PS Co-design framework will be generated. In addition, to support the identification of co-design candidates during the Co-Initiate phase, a simple tool helping the manufacturer to prioritise and visualise the resource efficiency, the design update rate and the effects overall of changes in P&PS will need to be developed. Besides, there also needs for a tool supporting the identification of the influence of design decision on resource consumption and the assessment of interrelation between product and production system design process.

### *2.5.5 Demonstrate the applicability of the proposed framework through case studies*

In Chapter 11, the proposed framework will be examined via a case study method. Tests will be carried out to determine how the proposed framework could be applied in practice. The implementation of the proposed developments will be applied in two case studies at industrial partners, producing simple and complex products using central design control and distributed design control. Finally, the test results will be utilised in refining and optimising the proposed framework.

## 2.6 CHAPTER SUMMARY

This chapter described the context of the research regarding the need to consider the production system in concert with product design, especially in light of the sustainability and resource efficiency aspect. Various research findings have also highlighted the need to support manufacturers in developing sustainable practices by collaborative P&PS design. Based on these considerations, the research questions, aim, objectives and scope of the thesis were identified. The following two chapters address research objectives 1 and 2 respectively. There, the state-of-the-art of the integrated design of P&PS is explored, as well as the individual areas of product design and production system design. This also covers the literature related to the sustainable design of P&PS

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# CHAPTER 3 STATE OF THE ART IN THE DESIGN OF PRODUCT AND PRODUCTION SYSTEMS

## 3.1 INTRODUCTION

This chapter examines the state-of-the-art in design processes which have been proposed to create a product and its production systems in order to understand design in theory and industrial practice. The three main sections cover the details of Product Design (PD), Production System Design (PSD), and the Integrated Design (ID). As the foundation of this chapter, these overviews include definition, methodology, and current practice for each design concept.

## 3.2 PRODUCT DESIGN

In light of the research focus, it is fundamental to understand the current state of research and industrial practice in the PD. The following sub-sections present a review of the literature related to existing concepts, models, methods, and industrial practices of PD.

### *3.2.1 An Overview of Product Design*

The term "product design" is widely understood as referring to "*the systematic activity necessary, from the identification of the market/user need to the selling of successful product to satisfy that need – an activity that encompasses product, process, people and organisation*" (Pugh 1991).

Ulrich and Eppinger (2003) have also defined "product design and development" as "*the set of activities beginning with the perception of a market opportunity and ending in the production, sale, and delivery of a product"*.

Moreover, various studies have also similarly defined PD, and generally, it could be described as 'a systematic process for guiding designers to transform customer requirements into a satisfying product or service'. According to these definitions, a traditional PD approach was commonly presented as a systematic process consisting of a step-by-step guide for designing a product. For example, a "total design activities model" consists of six main stages as shown in Figure 3.1 (Pugh 1991).

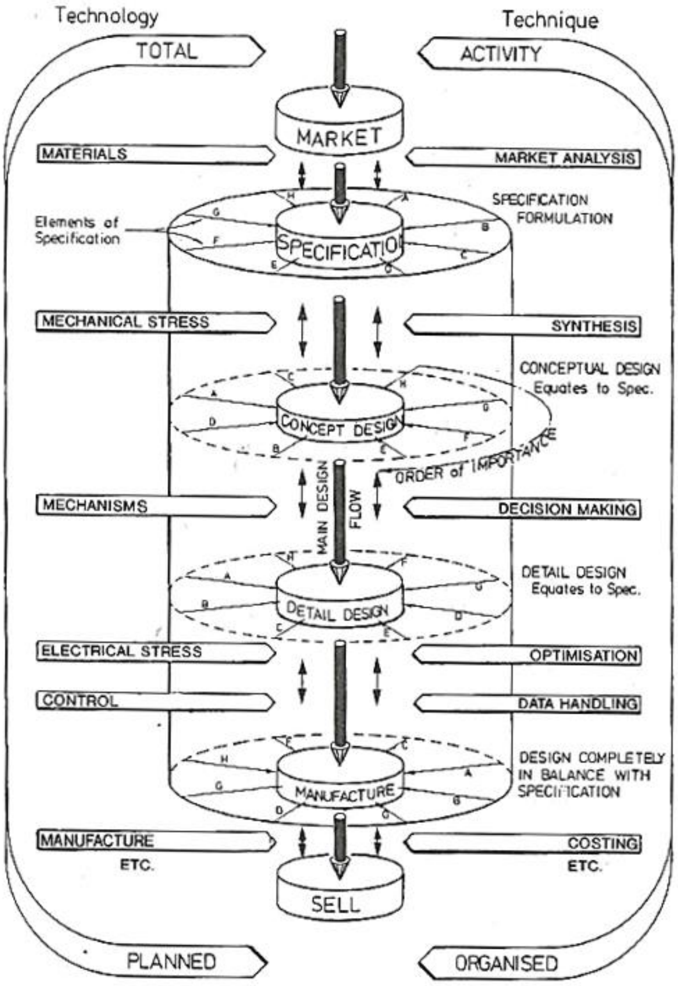


*Figure 3.1 – Pugh's Total Design Activities Model (Pugh 1991)*

Firstly, product designers start to transform customer needs into product specifications at the specification stage. Based on the clarified product specification, various product concepts are generated and evaluated during the concept design stage. After that, one of the product concepts is selected subject to the result of the evaluation. Then, design specifications of this selected design are defined and refined at the detailed design stage. Lastly, information about the completed product design is shared with manufacturers and retailers at the manufacture and sell stage, respectively.

In the same way, many PD approaches were also proposed in this stage-based manner. They have a generic core of stages because this provides clear boundaries for the design process and supports effective process management (Howard *et al.* 2008, Gericke and Blessing 2011). Examples of these approaches are shown in Table 3.1.

*Table 3.1 – A comparison of the engineering design process model (Howard et al. 2008)*

| Models | Establishing a need phase | Analysis of task phase | Conceptual design phase | Embodiment design phase | Detailed design phase | Implementation phase |
|---|---|---|---|---|---|---|
| Booz et al. (1967) | X | New product strategy development | Idea generation<br>Screening & evaluation | Business analysis<br>Development | Testing | Commercialisation |
| Archer (1968) | X | Programming<br>data collection | Analysis<br>Synthesis | Development | Communication | X |
| Svensson (1974) | Need | X | Concepts<br>Verification | Decisions | X | Manufacture |
| Wilson (1980) | Societal need | Recognize & formalize<br>FR's & constraints | Ideate and create | Analyze and/or test | Product, prototype, process | X |
| Urban and Hauser (1980) | Opportunity identification | Design | | Testing | | Introduction (launch)<br>Life cycle management |
| VDI-2222 (1982) | X | Planning | Conceptual design | Embodiment design | Detail design | X |
| Hubka and Eder (1982) | X | X | Conceptual design | Lay-out design | Detail design | X |
| Crawford (1984) | X | Strategic planning | Concept generation | Pre-technical evaluation | Technical development | Commercialisation |
| Pahl and Beitz (1984) | Task | Clarification of task | Conceptual design | Embodiment design | Detailed design | X |
| French (1985) | Need | Analysis of problem | Conceptual design | Embodiment of schemes | Detailing | X |
| Ray (1985) | Recognise problem | Exploration of problem<br>Define problem | Search for alternative proposals | Predict outcome<br>Test for feasible alternatives | Judge feasible alternatives<br>Specify solution | Implement |
| Cooper (1986) | Ideation | Preliminary investigation | Detailed investigation | Development<br>Testing & Validation | X | Full production & market launch |
| Andreasen and Hein (1987) | Recognition of need | Investigation of need | Product principle | Product design | Production preparation | Execution |
| Pugh (1991) | Market | Specification | Concept design | | Detail design | Manufacture<br>Sell |
| Hales (1993) | Idea, need, proposal, brief | Task clarification | Conceptual design | Embodiment design | Detail design | X |
| Baxter (1995) | Assess innovation opportunity | Possible products | Possible concepts | Possible embodiments | Possible details | New product |
| Ulrich and Eppinger (1995) | X | Strategic planning | Concept development | System-level design | Detail design | Testing & refinement<br>Production ramp-up |
| Ullman (1997) | Identify needs<br>Plan for the design process | Develop engineering specifications | Develop concept | Develop product | | X |
| BS7000 (1997) | Concept | Feasibility | Implementation (or realisation) | | | Termination |
| Black (1999) | Brief/concept | Review of 'state of the art' | Synthesis<br>Inspiration | Experimentation<br>Analysis / reflect | Synthesis<br>Decisions to constraints | Output<br>X |
| Cross (2000) | X | Exploration | Generation | Evaluation | Communication | X |
| Design Council (2006) | Discover | Define | Develop | Deliver | | X |
| Industrial Innovation Process 2006 | Mission statement | Market research | Ideas phase | Concept phase | Feasibility Phase | Pre production |

Besides this, a product design process can also be applied in different ways, based on the different aspects of a product (Ulrich and Eppinger 2003). For instance, in comparison with a simple product, a complex product which is comprised of various product parts is generally designed by multiple designers from various technical backgrounds. Therefore, the process for designing a complex product is considered as a complex design process that various activities are parallelly processed to design each product part. In the context of development time, a highly competitive market for technology products, such as software or mobile, also causes a differential application of design processes. Such a fast design and development process commonly has many repetitive prototypes and test cycles. These simple, complex and spiral design processes are illustrated in Figure 3.2.

In a context of the originality of the design, Pahl *et al.* (2007) have described a different application of embodiment design between original and adaptive design. For an original PD, embodiment design is regularly considered at the conceptual phase. This is to figure out how the physical product should appear through product architecture. In contrast, for adaptive design, the embodiment design has already been considered, and the interaction and interrelation of product parts are established in the original design. In this case, the embodiment of the adaptive design involves only some changed parts, and this is generally considered after the product concept is selected (See Figure 3.3). Such an adaptive design can still be very innovative, but it is not massively restructured (Otto & Wood, 2001).

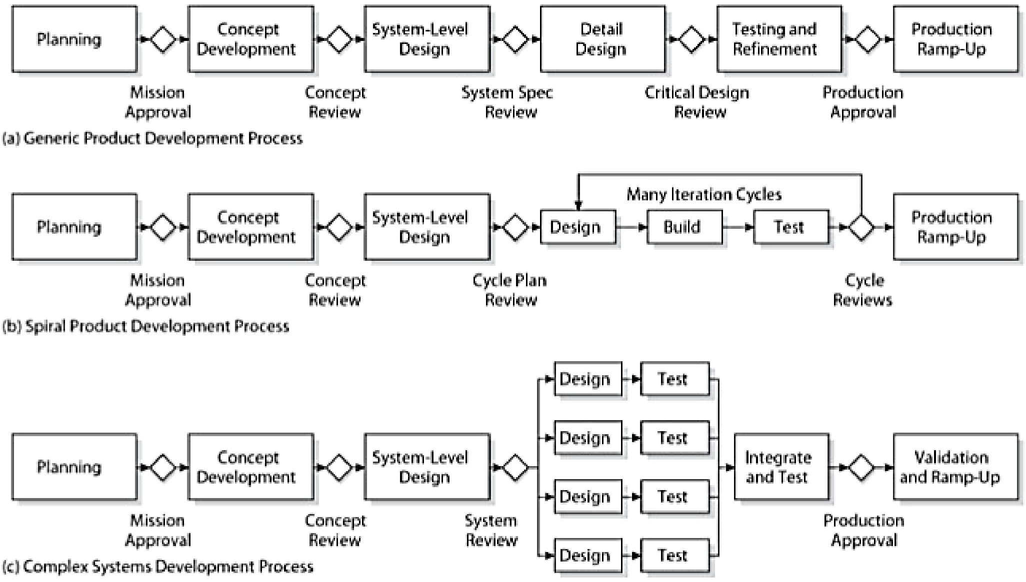


*Figure 3.2 – Process flow diagrams for three product development processes* (Ulrich and Eppinger 2003)

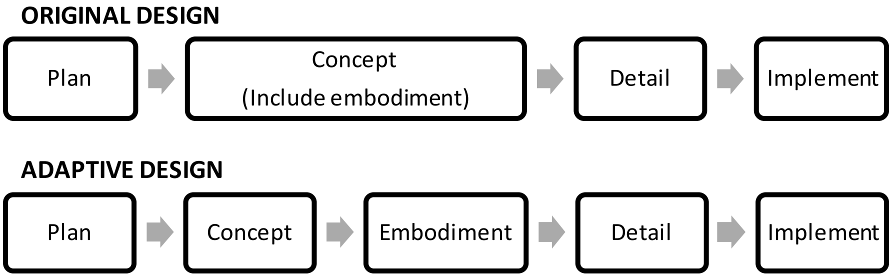


*Figure 3.3 – Different design processes for original and adaptive product design*

In addition to a stage-based approach, the focus of research in the PD expanded from descriptive approaches (basic process/model) to prescriptive ones, which had the purpose to not only organise the basic design, but also to improve the specific performance of a product or a design process (i.e. reducing development cost and time). For instance, a medical device is a safety product which is expected to work correctly without any errors. The PD process of a safety product therefore needs to support the final design's assurance. With this aim, NASA has developed the "Vee" model which focuses on product verification and validation for the software development (Forsberg and Mooz 1991), as presented in Figure 3.4.

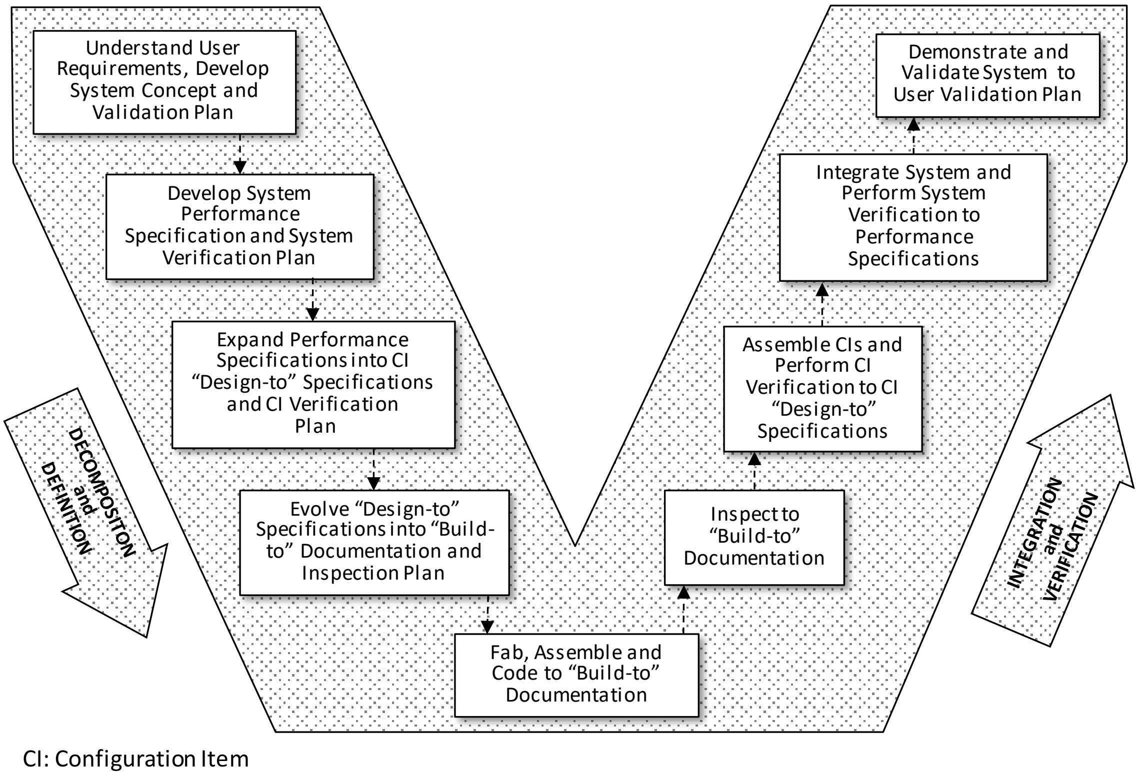


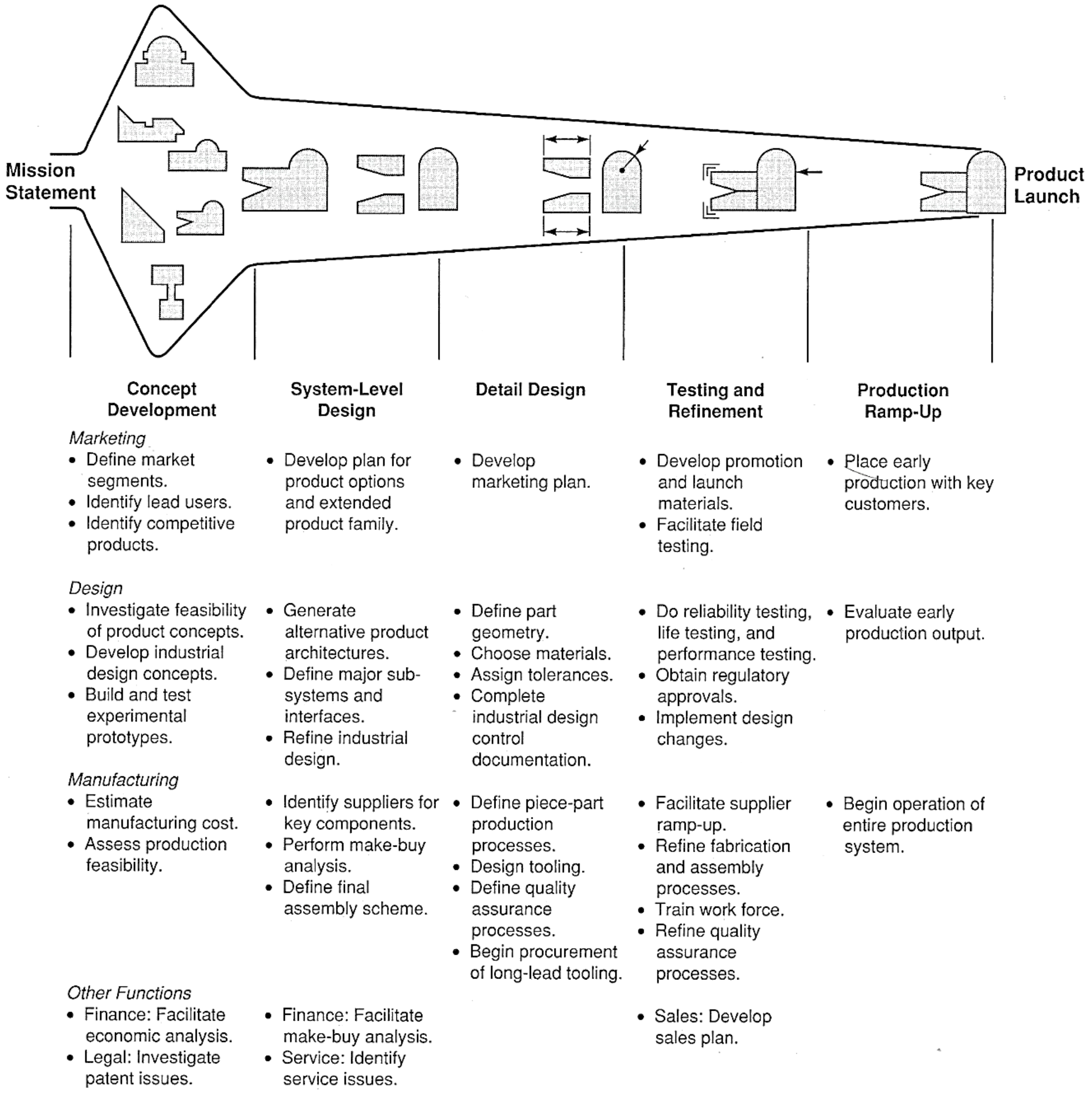
*Figure 3.4 – Overview of the Technical Aspect of the Project Cycle* (Forsberg and Mooz 1991)

In addition to this, Wynn & Clarkson (2005) have extensively studied existing PD processes, and some popular approaches have been classified based on different focuses as follows:

i. Pahl, Beitz, Feldhusen, & Grote (2007) presented a systematic approach which focuses on mechanical engineering design.

ii. With a similar emphasis, Ullman (2003) presented another mechanical engineering-focused approach which also included many examples of practical application in order to visualise a real-life design (Tomiyama *et al.* 2009)

iii. With focuses on the personal and disciplinary aspects, Ulrich & Eppinger (2012) presented a generic development process (see Figure3.5). This is to facilitate logical problem-solving in various backgrounds.



| | Concept Development | System-Level Design | Detail Design | Testing and Refinement | Production Ramp-Up |
|---|---|---|---|---|---|
| *Marketing* | • Define market segments.<br>• Identify lead users.<br>• Identify competitive products. | • Develop plan for product options and extended product family. | • Develop marketing plan. | • Develop promotion and launch materials.<br>• Facilitate field testing. | • Place early production with key customers. |
| *Design* | • Investigate feasibility of product concepts.<br>• Develop industrial design concepts.<br>• Build and test experimental prototypes. | • Generate alternative product architectures.<br>• Define major sub-systems and interfaces.<br>• Refine industrial design. | • Define part geometry.<br>• Choose materials.<br>• Assign tolerances.<br>• Complete industrial design control documentation. | • Do reliability testing, life testing, and performance testing.<br>• Obtain regulatory approvals.<br>• Implement design changes. | • Evaluate early production output. |
| *Manufacturing* | • Estimate manufacturing cost.<br>• Assess production feasibility. | • Identify suppliers for key components.<br>• Perform make-buy analysis.<br>• Define final assembly scheme. | • Define piece-part production processes.<br>• Design tooling.<br>• Define quality assurance processes.<br>• Begin procurement of long-lead tooling. | • Facilitate supplier ramp-up.<br>• Refine fabrication and assembly processes.<br>• Train work force.<br>• Refine quality assurance processes. | • Begin operation of entire production system. |
| *Other Functions* | • Finance: Facilitate economic analysis.<br>• Legal: Investigate patent issues. | • Finance: Facilitate make-buy analysis.<br>• Service: Identify service issues. | | • Sales: Develop sales plan. | |

*Figure 3.5 – A generic development process* (Ulrich and Eppinger 2003)

In Figure 3.6, the axiomatic design was established as a scientific design process which focuses on information and a relationship of function (Suh 1998, Tomiyama *et al.* 2009).

In this overview, many PD approaches have been proposed to support various applications based on different aspects of product and process performance. However, while these approaches have shared a similarity of definitions and the nature of the design process, they are far too general to support daily applications (Wynn and Clarkson 2005). Therefore, the following section further investigates PD in current practice.

### *3.2.2 Product Design in Practice*

various design dimensions such as success factors and tools should also be considered to implement PD successfully. This section therefore discusses the current practices of the PD through the application of design approaches, design tools and design success factors.

At present, many innovative companies still struggle in applying and improving their product design and development process. According to a Product Development and Management Association (PDMA) survey in 2012, there were only 24.6% of the companies whose design process performance was considered as the best practice and which successfully launched more than 82% of the new products on average during the last five years (Markham and Lee 2013). By contrast, all other companies (75.4%) were able to launch only 52.9% of new products on average. This research also found that the best-performing companies regularly deploy formal and cross-functional processes significantly more often than the rest (67% in the Best and 41.8% in the Rest). Therefore, the "lack of process vision" and "lack of knowledge of new product development best practices" were highlighted as the main problems in most design organisations (Costa *et al.* 2013). Besides, even though various design processes/approaches (mentioned in the

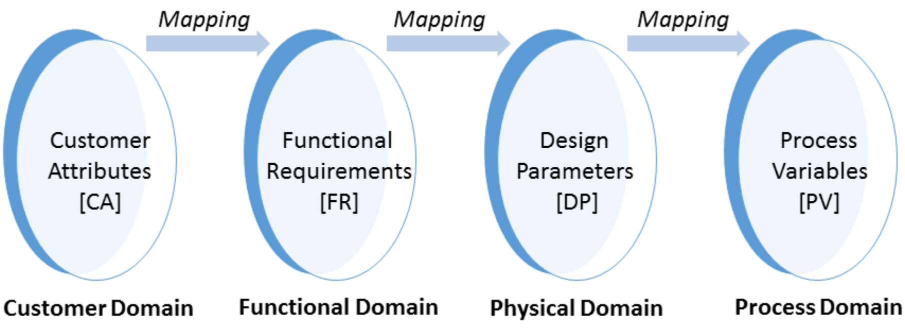


*Figure 3.6 – Four domains in axiomatic design (Suh 1998)*

the previous section), which have been proposed to support the adoption of a formal and structural design process, expected to mitigate these problems, these idealistic linear approaches were often used in education instead of industry practice (Wynn and Clarkson 2005, Howard *et al.* 2008, Tomiyama *et al.* 2009).

In order to identify the problems of the currently proposed approaches, the best-known design models have been analysed based on seven aspects Costa *et al.* (2015). In Table 3.2, the result shows that the existing models are unable to respond to sustainability (lack of consideration of factors such as eco-design, product service systems, and end-of-life).

*Table 3.2 – Design process exploration (adapted from Costa et al., 2015)*

| Aspects | Design process analysis | The potential improvement needed |
|---|---|---|
| **Discipline** | Most existing design models and approaches were proposed for designing a physical product in mechanical and electrical engineering areas | There are only a few approaches in the product service system area, which has become a trend at present |
| **Knowledge Area** | Addition to design knowledge, process design/engineering is often provided, and only some approaches give suggestions for managing a project, quality, marketing, communication, people and organisation | Most of the current approaches rarely include the management of the business process, supplier, service and sustainability |
| **Design stage** | Most of the approaches heavily detail the front-end stage until detailed design | There is a lack of knowledge regarding the last stage (end-of-life) |
| **Scope of development** | Product development focus | Lack of technology, service, and business development |
| **Design approach (i.e. Lean, Eco-design, IPD)** | IPD is the most popular approach | There still is a need for eco-design and product service system integration, which are rarely in existence |
| **Level of detail** | Most models provide high-level and basic information covering activity, method/technique, example and information | There is a lack of information about roles and metrics for measuring the performance of the product and process itself |
| **Implementation** | Most design approaches focus on designing an original product and exclude guidelines for implementation and maturity measurement | The future model should include a consideration of adaptive design, flexibility, implementation guide and maturity model |

This finding is consistent with that of Howard *et al.* (2008) who also pointed out that current approaches commonly focus on development projects initiated by market pull, excluding current circumstances like technology push.

Moreover, another difficulty in implementing design approaches has been raised for more than two decades. It has been stated that the challenge of design approach application is the focus on original design, although design practice needs support for the more frequent task of adaptive design (Maffin 1998, Wynn and Clarkson 2005).  Therefore, the usefulness of the existing design approaches is very limited since they focus more on the development of an original design's functions instead of the improvement of an adaptation design based on essential factors such as available resources and management conditions.

Besides, a lack of the management aspect in PD approaches has been agreed by many studies. For instance, Wynn and Clarkson (2005) mention that many product-focused approaches limit their usefulness because they exclude management aspects which are of significant importance for designers. These approaches do not explain the rationale of the proposed processes and don't provide enough support on how to perform design activities, only what to do (Gericke and Blessing 2011). Besides, an absence of a detailed guideline in these models leads to an inflexibility for a specific implementation at different companies (Costa *et al.* 2015). Hence, most of the well-known PD approaches are more suitable for providing basic design knowledge like product function than for representing the creative process in sufficient detail to support design activities (Maffin 1998, Wynn and Clarkson 2005, Howard *et al.* 2008, Tomiyama *et al.* 2009, Costa *et al.* 2013). In addition to these, some design approaches such as axiomatic design are too complicated and require substantial training to apply in practice (Meljer 2003, Thompson 2009).

Moreover, designing in industry practice which is routine in nature generally aims to achieve concrete performances such as cost, time and quality, rather than complete a new design. Hence, design methods that support decision making or design process modelling were more applied in industry practice because they are more flexible for different uses and able to satisfy a concrete goal (Clarkson and Eckert 2005, Tomiyama *et al.* 2009). Examples of these methods are Quality Function Deployment (QFD) or House of Quality, Design for X, IDEF0, Design Structure Matrix (DSM), and concurrent engineering.

In addition, although some of these methods were recognised to be useful in practice, they are not widely used in comparison to other design methods and tools. Fujita & Matsuo (2005) has investigated the implementation of the existing design methods and tools used in 118 industrial companies. The results revealed that these design methods (i.e. Failure Mode Effect Analysis, QFD and Design for X) are generally adopted in research and industrial practice because of their flexibility and simplicity in application. However, product designers are likely to apply support tools that can store, real-time update, and share product data and are also comfortable and flexible to use (Lutters *et al.* 2014). Therefore, design tools such as CAD, CAE, and simulation system tools are judged the most effective (see Figure 3.7).

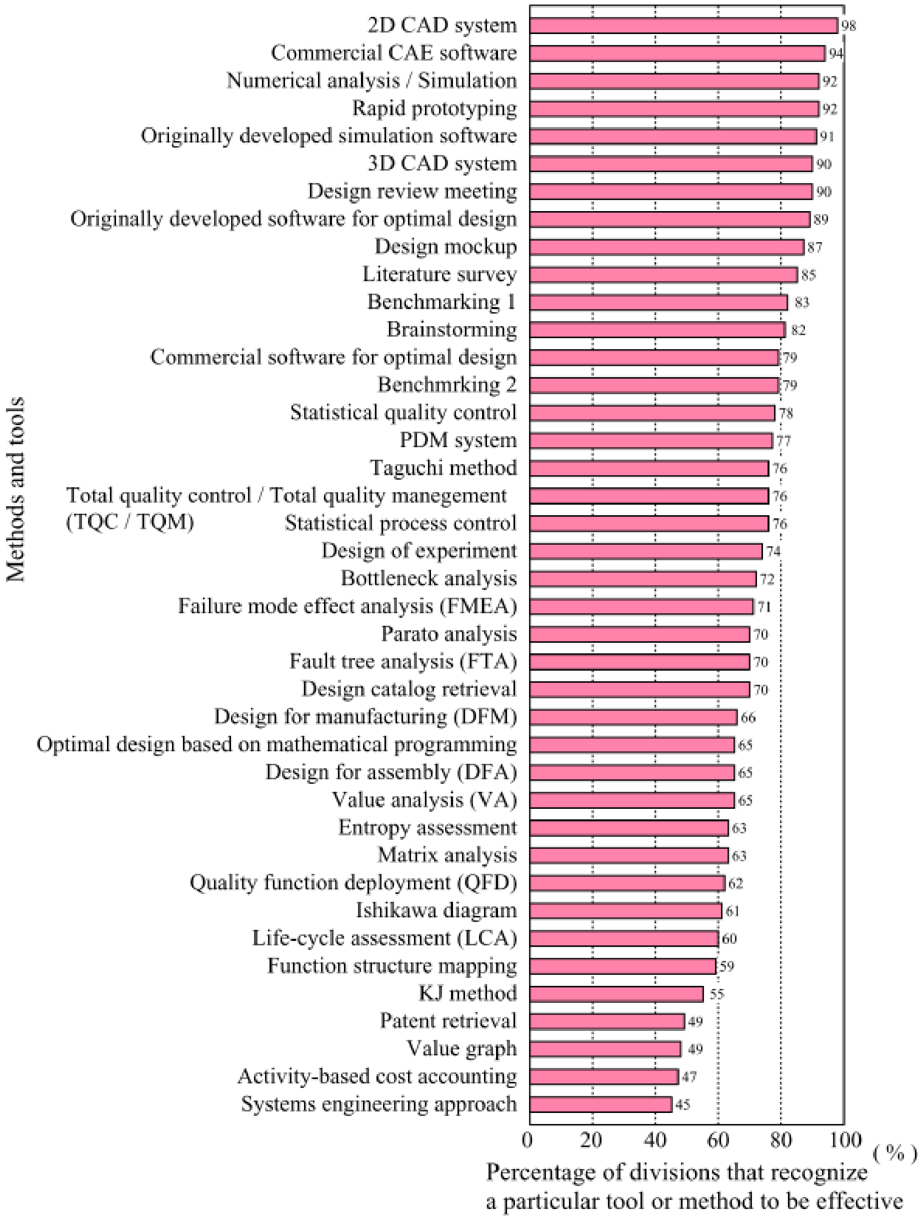


*Figure 3.7 – Effectiveness of tools and methods under their utilisation (Fujita and Matsuo 2005)*

In conclusion, to implement PD effectively, many companies currently confront the four main difficulties as listed in Table 3.3. To mitigate these, a company was suggested to follow a best practice PD process which (O'Donovan *et al.* 2005, Nicholas *et al.* 2011, Barczak and Kahn 2012, Kahn *et al.* 2012):

i. "cuts across organisational groups" and has clear go/no-go criteria for each design review
ii. is flexible and adaptable to apply to the different needs, size, and risk of each individual project
iii. is visible, well documented, and provide information- and knowledge-related design projects which are available to all designers and related stakeholders
iv. To achieve this, a manufacturing company was also recommended to focus on the critical success factors for PD implementation have been defined. These factors involving design organisation and management are communication, collaboration, information and knowledge distribution, performance measurement, and company culture (Nicholas *et al.* 2011, Kahn *et al.* 2012, Sheldrick 2015).

*Table 3.3 – Difficulties in Product design practice*

| **Difficulties in Product design practices** | **Authors** |
|---|---|
| **Original design focus** instead of an adaptive model | Maffin (1998),<br>Tomiyama et al. (2009),<br>Wynn and Clarkson (2005) |
| **Lack of knowledge** such as best practice, team-work, and legislative | Costa et al. (2013),<br>Costa et al. (2015),<br>Gericke and Blessing (2011),<br>Wynn and Clarkson (2005) |
| **Lack of flexibility, implementation and management guideline**s to serve a particular application (for a specific product, designer and company) | Costa et al. (2015),<br>Gericke and Blessing (2011),<br>Howard et al. (2008),<br>Maffin (1998),<br>Meljer (2003),<br>Thompson (2009),<br>Tomiyama et al. (2009),<br>Wynn and Clarkson (2005) |
| **Exclusion of sustainability and technology consideration** | Costa et al. (2015),<br>Howard et al. (2008) |

## 3.3 PRODUCTION SYSTEM DESIGN

Meyers and Stephens (2005) consider the term "**manufacturing facility design**" to refer to the activities (plant location, building design, plant layout, and material handling) for organising the company's physical facilities to promote the efficient use of resources such as human resource, equipment, materials and energy. In similar fashion, "**production development"** was defined by Bellgran and Säfsten (2010) as a concept for creating effective production processes and developing production ability to either improve existing systems or develop new ones. Many similar design concepts have used the term "production" and "manufacturing" as synonyms of one another. However, the concept of "manufacturing" is broader than "production" because it also involves managerial functions. As a part of the supply chain, the boundary of manufacturing is located between the suppliers and customers of a manufacturing company (Segreto and Teti 2014).

Therefore, the definition of "**manufacturing**" can be formulated as "*all activities within a company for design, material, supply, planning and production, to quality assurance, distribution, management, and marketing*" (Bellgran and Säfsten 2010).

Whilst, the term "**production or manufacturing production**" refers to *"the act or process (or the connected series of acts or processes) of actually physically making a product from its material constituents, as distinct from designing the product, planning and controlling its production, assuring its quality"* (Alexopoulos *et al.* 2014).

Based on the scope of this research, this section reviews research papers related to Production System Design (PSD) which address approaches for designing and developing production systems as an organisational unit of manufacturing dealing with parts production (fabrication) and the assembly of products (see Figure3.8).

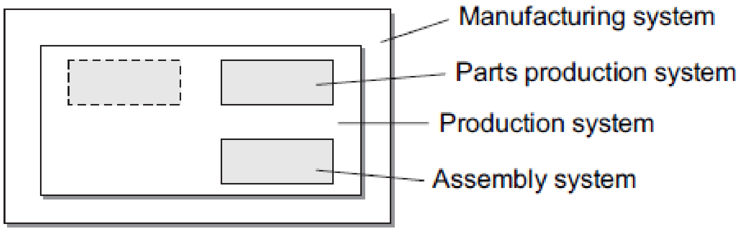


*Figure 3.8 – A hierarchical perspective on a production system (Bellgran and Säfsten 2010)*

### *3.3.1 An Overview of Production System Design*

The key reason for developing a new production system is **the introduction of new products or product families** which, for various reasons, it was not possible to produce in the existing systems. Moreover, the changes might be caused by an improved working environment, increases in capacity, new environmental legislation, market change or technology development (Bellgran and Säfsten 2010). Whatever the motivation for development, a newly developed production system should contribute to the effective interaction and information flow of materials, human resources, equipment, and investment in order to achieve the manufacturing business's goal. In this light, the purpose of the PSD process is to enhance system quality, system design, reduce system cost and cycle time, verify all system requirements, and validate the design outcome (Wu 1992).

Most of the traditional PSD methodologies present a holistic process comprised of a set of stages, as shown in Figure 3.9. These design processes generally initiate system design by realising system requirements. Continuously, the requirements are translated into a conceptual system and are structured at the system configuration.

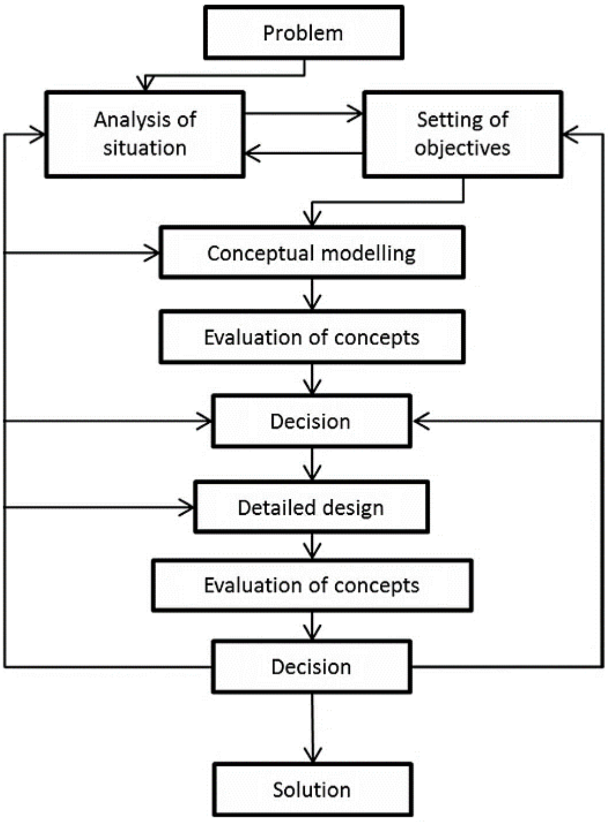


*Figure 3.9 – A structure of the product system design approach (Wu 1992)*

Then, all details of the system, such as the material handling equipment, service unit, and system layout, are decided at the detailed design stage. Before starting production, product quality, system accuracy and system efficiency are evaluated and confirmed at the production ramp-up step. With this pattern, it can be seen that there is a similarity in the process structure of PD and PSD. This also explains why product design approaches were sometimes applied to the designing of a production system (Gräßler and Yang 2016). Likewise, production systems were considered to be *"complex and long-life products which have to be adapted to the needs of markets, production programs and technologies"* (Westkämper 2007).

In addition, other similar PSD approaches which offer the different advantages and drawbacks are exemplified in Table 3.4. For instance, Fisher issued AI-based methodologies with the focus on economic and currently emerging technologies (Fisher 1986). Moreover, some approaches such as the advanced manufacturing system consider the redevelopment stage after the operation phase. This method however has no guidance for tracking emerging technology, considering investment, or providing the most suitable type of manufacture (Doumeingts *et al.* 1987). Moreover, Gu *et al*. (2001) utilised axiomatic design to produce process flow design rather than holistic system design. In a different fashion, Meyers & Stephens provide very detailed guidelines for manufacturing facility design which is very useful for the first system establishment (Meyers and Stephens 2005). In addition to this, Bellgran and Säfsten (2010) proposed the production system development process for either creating an original or improving the existing system (see Figure 3.10)

Based on these previous publications, the production system design approaches were not widely developed comparing to the product design approaches. This finding was also reported by Bellgran and Säfsten (2010) who asserted that a lack of development in PSD approach was because of the limited requirement to improve production system design from relevant stakeholders. Besides, these PSD approaches were rarely implemented in industries due to several reasons which are described in the next section.

Table 3.4 – A comparison of production system design processes

| Author | | Fisher (1986) | Doumeingts, et al. (1987) | Pugh (1991) | Wu (1992) | Suh (1997) | Rao (1999) | Gu et al (2001) | Mayer & Stephens (2005) | Bellgran and Säfsten (2010) |
|---|---|---|---|---|---|---|---|---|---|---|
| **Model** | | **AI-based methodology** | **Advance Manufacturing System (AMS)** | **Process design core** | **Design Approach** | **Axiomatic Design** | **A genetic algorithm based approach** | **Axiom-Systematic Design** | **The manufacturing facility design procedure** | **Production system development process** |
| **DESIGN STAGE** | **Establish Need** | Determine product flow and nonflow constrain. Combine flow and nonflow relationship | Analysis Phase | Process requirement | Problem generate/Analysis of stiuation/Setting of objective | The recognition of a societal need | System conceptualization | Design requirement of Manufacturing system | Step 1 | Management and control |
| | **Planning (System Requirement)** | | | Specification | | Funtional requirement and Constrain analysis | | | Step 2-15 | Preparatory design |
| | **Conceptual system** | Select layout generator routine, Invoke layout generator | Conceptual Modelling | Conceptual design | Conceptual modelling & Evaluate concept | Idea generation | System Structuring | Conceptual Design of Manufacturing System | Step 16-19 | Design of conceptual production system |
| | **System configuration** | | Structural Modelling and functional specifiaction | | Detail design and Concept Evaluation (Meet requirement/financial improvement) | | | Configuration design (Layout design) | - | Evaluation of conceptual production systems |
| | **Detail system** | Analysis & Modification | Operational Specification | Detail Design | | Idea Analysis and Tests | System Configuration | Detail design of manufacturing system | Step 20-21 | Detail design of chosen production system |
| | **Installation** | Select best current layout and applying | Implementation phase | Procure/Manufacture | - | - | System Implementation | - | Step 22 | Realisation and planning |
| | **Operation** | - | Operation phase | | - | - | System Operation | - | Step 23 | Start-up |
| | **Redevelopment** | - | Development phase | | - | - | System | - | Step 24 | - |

*** A 24-step design process by Meyers & Stephens,2005**

1. Determine what will be produce
2. Determine how many will be made per unit time
3. Determine what parts will be made or purchased
4. Determine how each part will be fabricated
5. Determine the sequence of assembly
6. Set time standard for each operation
7. Determine the plant rate (takt time)
8. Determine the number of machine needed
9. Balance assembly line or work cells
10. Study the material flow patterns to establish the best flow
11. Determine activity relationships
12. Layout each work station
13. Identify needs for personal and plant services
14. Identify office needs.
15. Develop total space requirements
16. Select material handling equipment
17. Allocate the area according to the space needed
18. Develop a plot plan and the building shape
19. Construct a master plan of all selected manufacturing facility
20. A master plan review
21. A master plan approval
22. Install the layout
23. Start production
24. Adjust as needed and finalise project report and budget performance

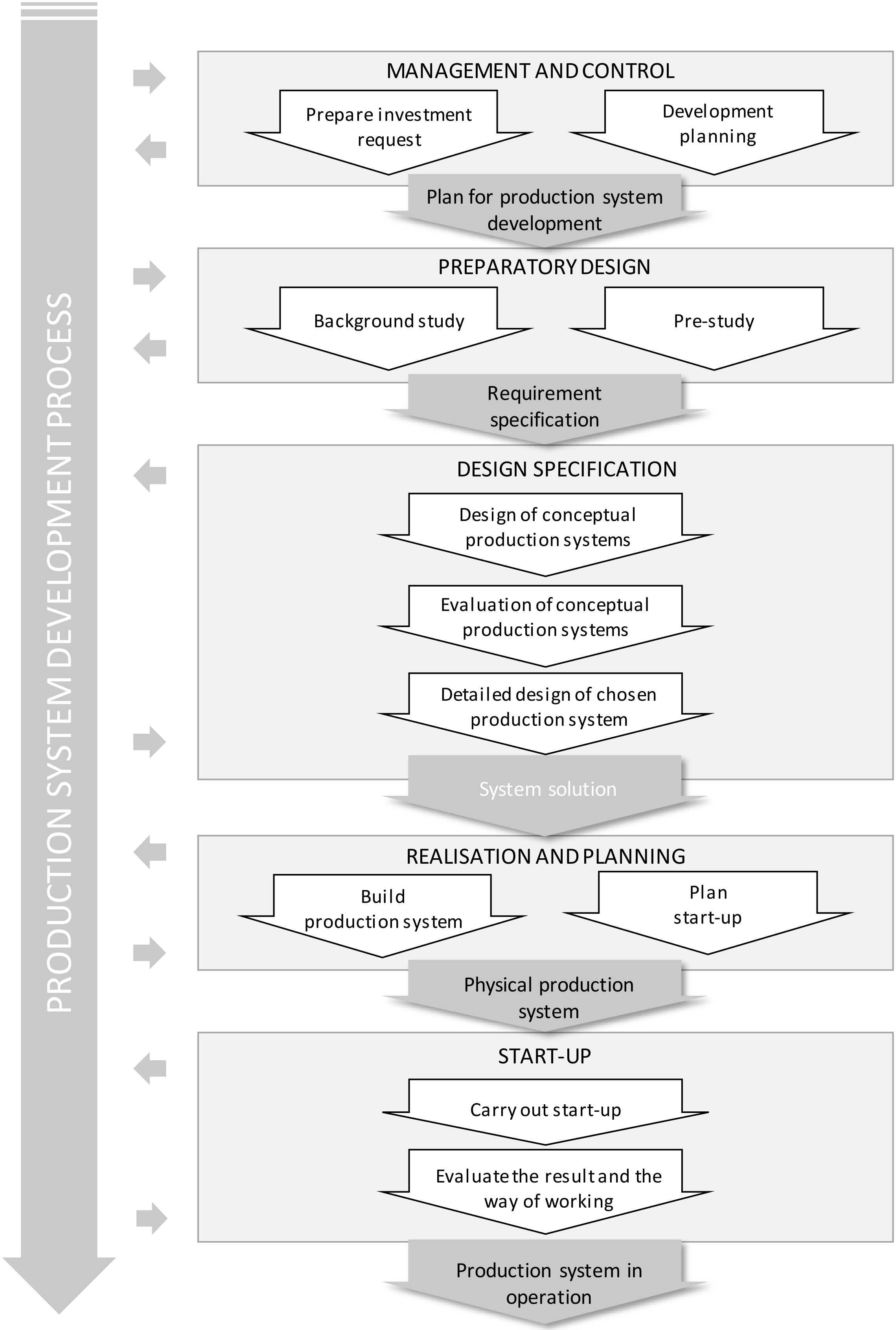


*Figure 3.10 – Description of a way of working with production system development* (Bellgran and Säfsten 2010)

### *3.3.2 Production System Design in Practice*

It has been reported that many of the traditional PSD approaches, as exemplified in the previous sub-section, were rarely adopted in industry practice (Alves and Carmo-Silva 2009, Bellgran and Säfsten 2010, Rösiö and Säfsten 2013).

This is due to the limitations of PSD approaches, as the existing approaches lack detailed guidelines to simplify implementation (Bellgran and Säfsten 2010, Rösiö and Säfsten 2013). In addition, some manufacturers have negative perceptions regarding ineffective and inefficient PSD approaches owing to the ways these approaches have been misused. Such implementation typically attempted to apply PSD approaches for tackling all complex design problems, despite the fact that PSD was designed to show the way to reach design solutions, not to resolve problems (Alves and Carmo-Silva 2009).

Apart from these reasons, current manufacturers in both developed and developing countries seek methodologies that adapt existing production systems rather than build new ones (Yang *et al.* 2015). In response, various design approaches for configuration were proposed and concluded in Alves and Carmo-Silva (2009). For instance, Hyer and Wemmerlov (2001) proposed a thirteen-step framework for preparing and replacing an existing production system with cellular manufacturing. Based on technology advancement, a virtual reality framework was also presented to support the adaptation and improvement of the current production system (see Figure 3.11).

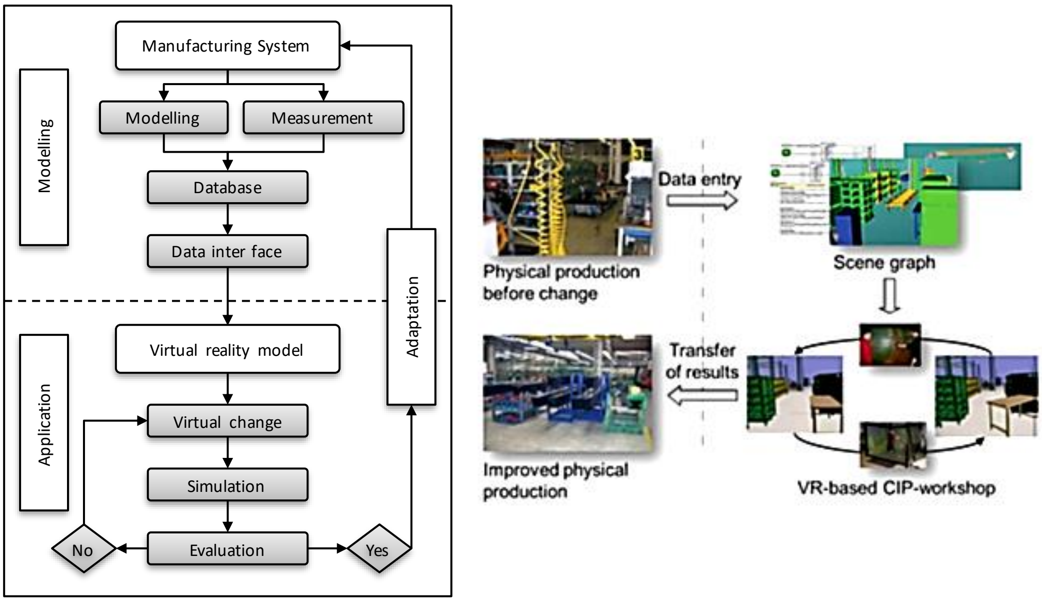


*Figure 3.11 – Workflow of virtual reality framework and virtual reality-based continuous improvement process workshop* (Yang *et al.* 2015)

Importantly, it has been underlined by various researchers that many existing PSD approaches were unable to respond to all present and future challenges. These challenges are based on the increasing requirements of the product, market, and technology aspects. First and most importantly, a design of production system needs to respond necessary requirements of products and manufacturing business such as product constraints (i.e. function and quality), restrictions and legislative requirements (i.e. health and safety) as well as cost and time reduction (Alves and Carmo-Silva 2009, Verbeek 2013, Gräßler and Yang 2016). These basic needs used to be effectively managed by traditional lean manufacturing (Bi 2011).

In addition to these requirements and higher market competition, the design of the production system was focused on responsiveness. Thus, a reconfigurable manufacturing system was presented to support better, faster and inexpensive design and production of high-variety products (Mehrabi *et al.* 2000). This reconfigurable manufacturing system was proposed to provide various responsibility, i.e. changeability, flexibility, reconfigurability and adaptability into traditional production system (Koren and Shpitalni 2010, Rogalski 2012, Hermann *et al.* 2016). Moreover, these abilities also include the other key characteristics of a reconfigurable manufacturing system as depicted in Figure 3.12. It was also highlighted that even though responsiveness has highlighted reconfigurability as a key to future manufacturing for more than a decade, a truly responsive design process and reconfigurable manufacturing system still does not exist (Garetti and Taisch 2012).

Most importantly, under the critical environmental issue at present, manufacturing businesses could be able to satisfy all product and production system demands and mitigate the limitations on natural resources.

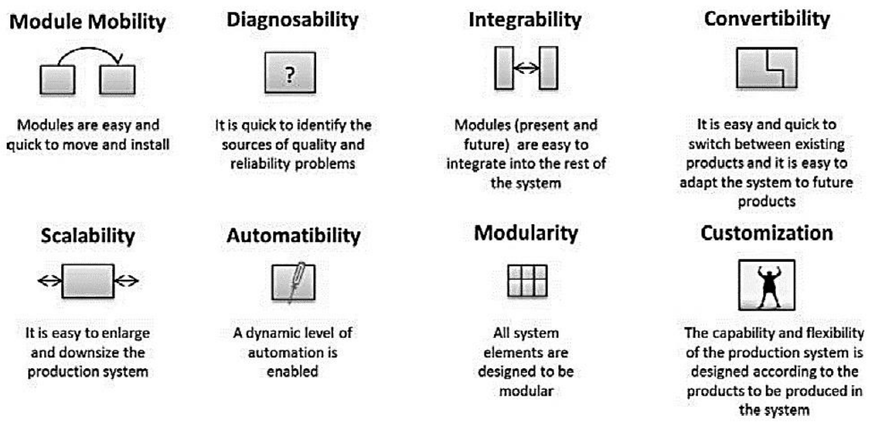


*Figure 3.12 – Reconfigurability Characteristics (Rösiö and Säfsten 2013)*

Attention has been paid to environmental sustainability in manufacturing for more than two decades. with the growing awareness of this issue, manufacturers are expected to be more responsible in their products and manufacturing systems and to achieve ‘sustainable manufacturing’, where ecological and social aspects are considered together with the traditional economic mindset (U.S Department of Commerce 2013). More recently, to move forward to the industry 4.0 in the near future, advanced manufacturing technology is necessitated for the achievement of all the above requirements. This is to gain information accessibility and interconnection, to support technical analysis, and to assist faster and decentralised decision making (Hermann *et al.* 2016).

In order to satisfy all of these requirements, there is a need for new PSD approaches which should:

i. Be represented as a holistic and systematic design process which provides clear guidance and includes up-to-date requirements in consideration (Saxena and Jain 2012, Rösiö and Säfsten 2013, Verbeek 2013, Gräßler and Yang 2016).
ii. Provide detail guidance supporting both cases of an original and adaptive PSD.
iii. Aid the faster development of production systems (Alves and Carmo-Silva 2009)
iv. Initiate the consideration of all critical requirements, which are generally considered at a later stage, at an early design stage (Mehrabi *et al.* 2000, Gräßler and Yang 2016).
v. Include the interdisciplinary collaboration between PD and PSD as well as related stakeholders. This is required not only to provide information accessibility and knowledge interchange but also to mitigate rising complexity under the limited cost and time of development (Martin and D’Acunto 2003, Black 2007, Verbeek 2013, Gräßler and Yang 2016).

The need for early consideration, information and knowledge availability, and interdisciplinary collaboration has been recognised for a long time. The arrangement of these factors was generally delivered through the concept of integrated design, which is explored in the following section.

## 3.4 INTEGRATED DESIGN

With regard to technological advancement and higher competition in the manufacturing sector, designers have been struggling to manage a more complex product with limited time during a shorter design and development phase. To tackle this situation, a number of studies have proposed a concept of the Integrated Design (ID) by including production system considerations into the product design process. Hence, this section presents an overview of existing ID concepts as well as investigates how these concepts and approaches have been developed and used in academic and industry contexts at present.

### *3.4.1 An Overview of Integrated Design*

Production system design is typically driven by the specific requirements of an existing and/or predesigned product. Referred to as the "throw over the wall" concept, this often causes long lead time, increased development costs, low product quality, and a frequent need for redesign of products and/or production systems (Spencer 1990, Otto and Wood 2001). To mitigate these difficulties, it has been highlighted that the product and its production system should be simultaneously considered at an early stage of the product design process (See Figure 3.13), because approximately 70-80% of the product performance, producibility and life-cycle costs are decided at this stage (Abdalla 1999, Howard and Lewis 2003). Therefore, Concurrent Engineering (CE) was proposed with the aim of:

> *"having integrated, concurrent design of products and their related processes, including manufacture and support. This approach is intended to cause the developers, from the outset, to consider all elements of the product lifecycle from conception through disposal, including quality, cost, schedule, and user requirements"* (Winner *et al.* 1988).

Following this key proposal, many studies also introduced different integrated approaches using different terms, such as Simultaneous Engineering (SE), Integrated Product-Process Development (IPPD), Integrated Product Development(IPD), Integrate Product And Process Design And Development ($IP^2D^2$), and Design for Manufacturing (DfM) (Andreasen and Hein 1987, Winner *et al.* 1988, Pugh 1991, Shunk 1992, Gerwin and Barrowman 2002, Magrab *et al.* 2009, Boothroyd *et al.* 2011). One of these is exemplified in Figure 3.14.

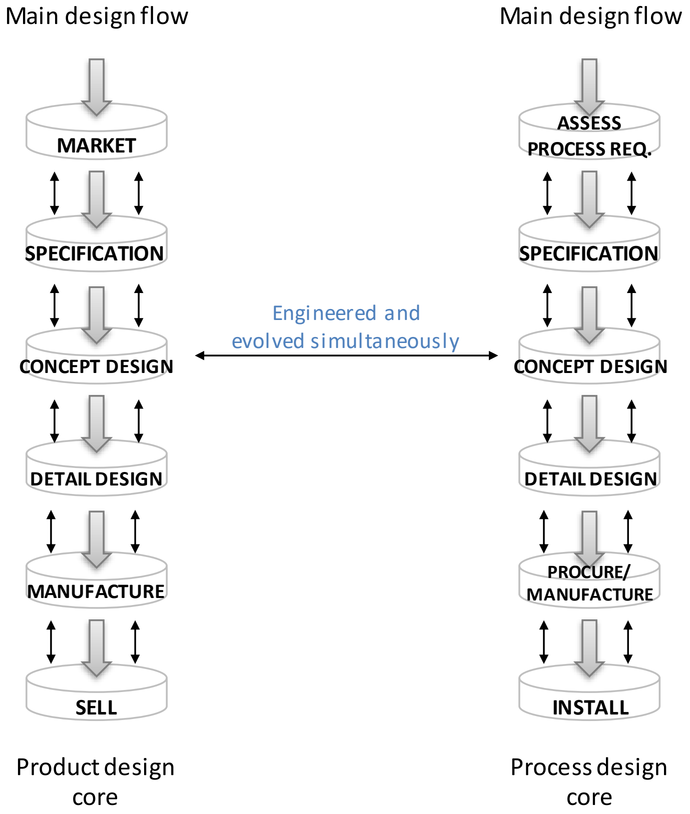


*Figure 3.13 - Industry is moving to simultaneous engineering to survive in all product and technology areas (Pugh 1991)*

Regarding the literature, much of the existing research in the integrated design area assumes the importance of four main characteristics which lead to the success of integrated design (See Figure 3.15). These characteristics are encouraging parallel activities, considering critical issues early in

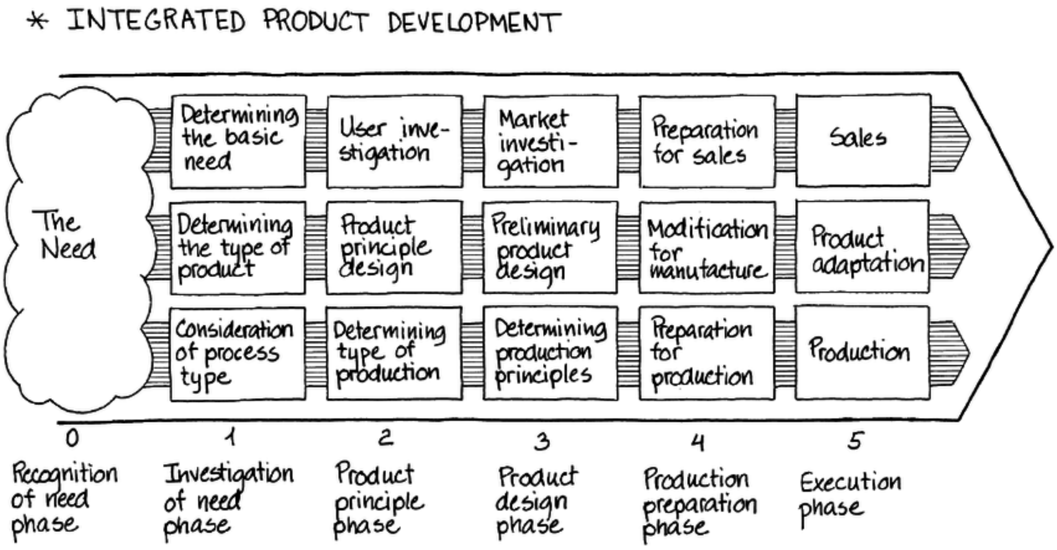


*Figure 3.14 – Integrated Product Development (Andreasen and Hein 1987)*

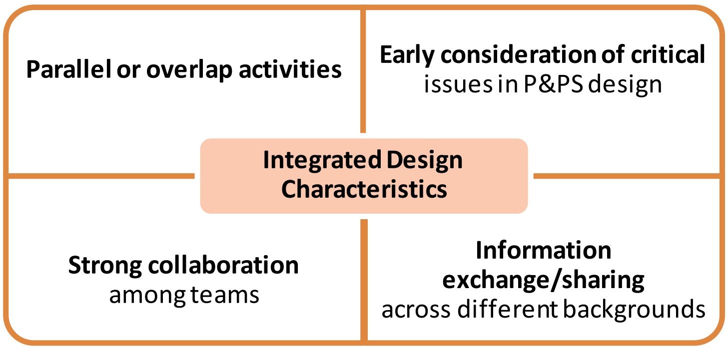


*Figure 3.15 – Four main characteristics of the integrated design concepts*

design, exchanging information and maintaining collaboration between teams (Gerwin and Barrowman 2002, Bhuiyan *et al.* 2006). To address these, relevant publications were reviewed based on four corresponding research themes: integrated design process, specific improvement of design process performance, technical tools to support information sharing/exchange, and strong collaboration.

### *3.4.1.1 Theme I: Integrated Design Process*

Firstly, the **"integrated design process"** such as IPD by Andreasen and Hein (1987), as well as the Generic Product Development Process (GPDP) by Ulrich and Eppinger (2003) are generally represented in the context of integration of parallel activities from different processes, e.g. marketing, product design, and production development. These management-level approaches generally suggest ways in which an integrated design can be managed through step-by-step activities performed by different stakeholders. Some of the approaches also suggest that an integrated process needs other integrated design methods and tools related to the other themes. Other concepts which also fall under this theme are SE (Pugh 1991), CE (Winner *et al.* 1988), IP$^2$D$^2$ (Magrab *et al.* 2009), Early Manufacturing Involvement (EMI) (Ettlie 1995), and Integrated Development Process of Products and Production systems (IDPPP) (Stoffels and Vielhaber 2016).

### *3.4.1.2 Theme II: Specific Improvement of Design Process Performance*

Under this theme, the proposed methods and tools commonly utilise one or two integrated design characteristics for enhancing the specific performance of a product, a production system and/or a development process, without any guidance on collaboration among design teams. For example, DfM and Design for Assembly (DfA) are also categorised as integrated design methods because they have been proposed to improve manufacturability and assemblability of products by embedding manufacturing information and knowledge into the product design process (Tomiyama *et al.* 2009, Boothroyd *et al.* 2011).

Based on the integration of the manufacturing and verification aspects, the design guideline collaborative framework was created to extend the application of DfM guidelines, applying them not only to product design but also to production process reconfiguration (Filippi and Cristofolini 2009). Likewise, traditional Quality Function Deployment (QFD) has been applied to present PD and PSD specifications to negotiate preferences between design and production system by product designers, instead of collaborative consideration by both parties (Lu *et al.* 2007).

In light of technology improvement, the DfA and DfM analytical tools were developed to support design engineers to faster evaluate and improve design concepts through information sharing. Examples of these analytical software packages are DFMA, SEER DFM and LASer software (Otto and Wood 2001). Besides this, also in this category are mathematical modelling tools which aim to structure the production or re-engineering process using a genetic algorithm in order to minimise production cost and time (Tomiyama *et al.* 2009). For instance, Bryan *et al.* (2013) proposed a genetic algorithm model to find the product family and reconfigurable assembly systems design that would result in maximum profits. Similarly, based on a DSM tool, Tang's model aims to re-engineer the existing design process to enhance concurrency among design activities for reduction of product development time and cost (Tang *et al.* 2000).

In addition, the proposed integrated design processes and methods related to these first two themes have been presented based on implementation criteria and stage of application, as depicted in Figure 3.16. Specifically, CE, IPD and the generic product development process have continuity in integration because these models provide guidance for integrating product and manufacturing system through all stages of the design process. On the other hand, the DfA and DfM methods are developed for implementation only with the complete design concept at a late stage of the design process.

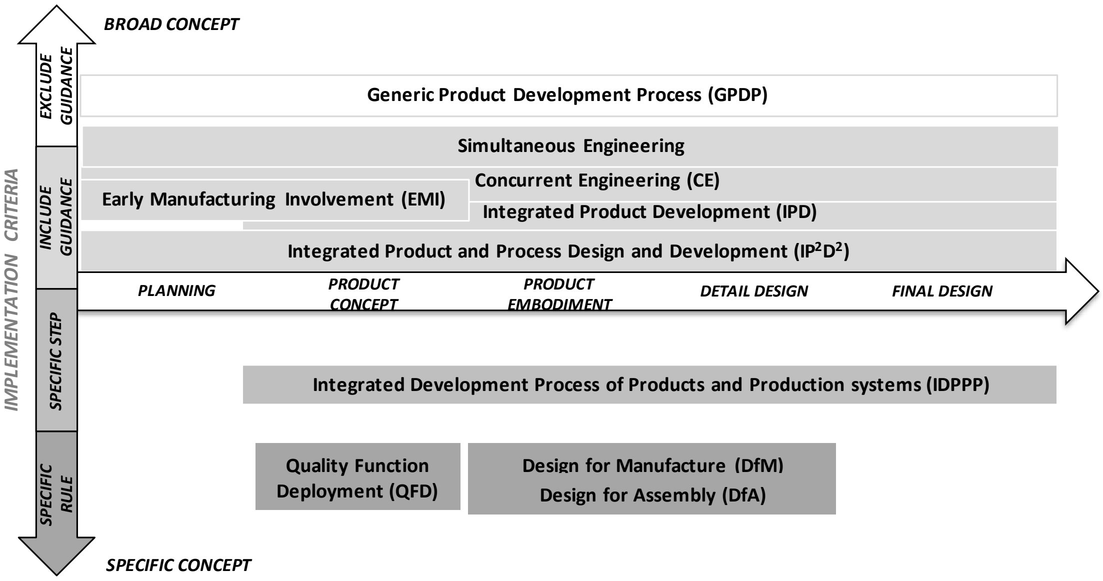


*Figure 3.16 - The existing concepts of integrated design processes and methods (implementation criteria vs applied stage)*

### *3.4.1.3 Theme III: Technological Tools to Support Information Sharing/Exchange*

The integrated design in this theme is often proposed in the context of design tools supporting information exchange across internal and/or external manufacturing organisations. They can be classified into information modelling and knowledge management tools.

First, **Information Modelling or language tools** (IM) are developed for modelling and representing knowledge and information of facilities, physical objects, or activities. Therefore, IM tools such as ontology engineering and Integrated computer-aided manufacturing DEFinition (IDEF) are widely applied in product and manufacturing system design. Another well-known tool is Computer Aided Design (CAD), which is *"an application using interactive graphic techniques that are used in translating a requirement or concept into a design"*(Stark 2011). Manufacturing businesses generally apply 3D CAD in product design and development to reduce development cost and time. In detail, CAD allows a designer to change, edit and improve the design faster and easier. Moreover, it also supports prompt communication with related stakeholders such as manufacturing system designers and suppliers. Based on the potential benefit of early design consideration, some IM tools have been developed to support the integration of manufacturing information at an early design stage (Swift and Booker 2013). Some of these tools have been traditionally proposed based on CAD or Computer Aid Manufacture (CAM); in this way, product designers can obtain production process information on a daily basis without any changes (Lu *et al.* 2007, Mountney *et al.* 2007). Similarly, IM tools have also been further developed to support design selection by providing information related to resources, materials and the production process (Howard and Lewis 2003, Feng 2005). This also includes work in feature-based design, which is developed to integrated data from CAD, CAM, and/or Computer-Aided Process Planning (CAPP), such as the software for process planning of machining processes with optimisation using genetic algorithms by Kingsly Jeba Singh and Jebaraj (2005). This was developed for sharing design information in computer numerical control from the conceptual to manufacturing phases. Likewise, Šormaz *et al.* (2010) proposed an approach to integrate key product realisation (complete CAD of product, CAPP process planning, scheduling, and flexible manufacturing system simulation) in order to determine the optimal process planning using the least development time.

**Knowledge Management Tools** such as Product Data Management systems (PDM) or Enterprise Resource Planning (ERP) have been developed for managing data like CAD, Material Requirements Planning, or Manufacturing Resource Planning. These software systems are typically developed with the aim of providing information to the entire organisation. Such information, structurally and systematically handled by the system, proceeds from customer order to manufacturing and final delivery (Stark 2011). For instance, Giovannini et al. (2012) developed a knowledge-based system which includes sustainability knowledge by using PDM for supporting product designer and process planning in a manufacturing business. These applications of knowledge management are supported by ISO 10303 or STEP (STandard for the Exchange of Product model data). STEP was developed for exchanging and standardising a wide range of product-related data throughout the product lifecycle. In other words, STEP can support product and production designers in exchanging data about products between different CAD systems, or between CAD and downstream application systems (Pratt 2001).

#### *3.4.1.4 Theme IV: Strong Collaboration*

The International Journal of Collaborative Engineering has broadly defined collaborative activity as "the interaction of engineering collaboration, when several related stakeholders resolve conflicts, bargain for individual or collective advantages, agree upon courses of action, and/or attempt to craft joint outcomes which serve their mutual interests" (IJCE 2007). It is also widely known that collaboration can cause additional complexity due to a difference and variety of individual collaborative objectives and benefits, the interfaces between decision/negotiation processes, and the integration of social/technical aspects of engineering activities.

Hence, a **'Strong Collaboration'** has been introduced to discover the fundamental success factors, as well as the risks of collaboration and negotiation in product development and to identify how these can be effectively managed and enhanced. Various studies on this theme have been proposed under the concept of Collaborative Product Development (CPD), which is recognised as an extension of ID by considering a collaboration of both internal (also known as a cross-functional team) and external organisation (Gerwin and Barrowman 2002, Luo *et al.* 2010). In this regard, Luo et al. (2010) have indicated that a higher level of internal coordination leads to the effective integration of skills and knowledge from different backgrounds, productive product development, and better external collaboration.

In addition, many researchers and practitioners have highlighted that **communication** is one of the critical success factors of collaborative design (Maier *et al.* 2008, Tomiyama *et al.* 2009). For this reason, some of these studies focused on different aspects of communication, such as influential collaboration factors, information exchange and cognitive behaviour in team communication during the development phase. Red *et al.* (2013) reported that the effectiveness of collaboration could be enhanced through informal communication rather than formal activities such as meetings. Besides, Maier *et al.* (2008) has isolated nine key factors influencing communication in product development process: mutual trust, collaboration, roles and responsibility, project reviews, availability of information about product specifications, handling of technical conflicts, ability to recognise what information the other party needs, autonomy of task execution, and an overview of sequence of tasks in the design process. In a review-based study, Büyüközkan and Arsenyan (2012) similarly reported that **trust** and **communication** are the most highlighted success factors among a range of essential collaboration factors (see **Error! Reference source not found.**). Even though trust is more often mentioned in the literature than communication in the past decade, achieving it is often impossible without effective communication and information sharing (Bstieler 2006, Bunduchi 2013). In order to enhance collaboration performance, it can be concluded that these underlined success factors should not be individually considered, because they also correlate with and influence one another.

*Table 3.5 – Key factors of CPD motivation, success, and risks (Büyüközkan and Arsenyan 2012)*

| Key factors of Collaborative Product Development | | |
|---|---|---|
| **Motivations** | **Success** | **Risk** |
| 1.Sharing risks<br>2.Reducing cost<br>3.Technology<br>4.Knowledge<br>5.Experience<br>6.Reducing time-to-market<br>7.Market opportunities and competition<br>8.Expanding product family and innovation<br>9.Administrative initiative and corporate culture<br>10.Maintaining sustainability | 1.Trust<br>2.Communication<br>3.Partner selection and preparation<br>4.Product quality<br>5.Attaining the main goal<br>6.Commitment, interest and inter-team relationships<br>7. Fairness<br>8.Reciprocity<br>9.Flexibility<br>10.Learning<br>11.Leadership<br>12.Experience<br>13.Alignment<br>14.Information and risk sharing | 1.Leakage of a firm's skill<br>2.Experience and knowledge that may form the basis of its competitiveness<br>3.Additional financial and time costs incurred in managing the collaboration<br>4.Loss of direct control by an organization over the product development process<br>5.Poor communication within and across organizational boundaries<br>6.Documentation problems<br>7.Opportunity cost<br>8.Trust issues |

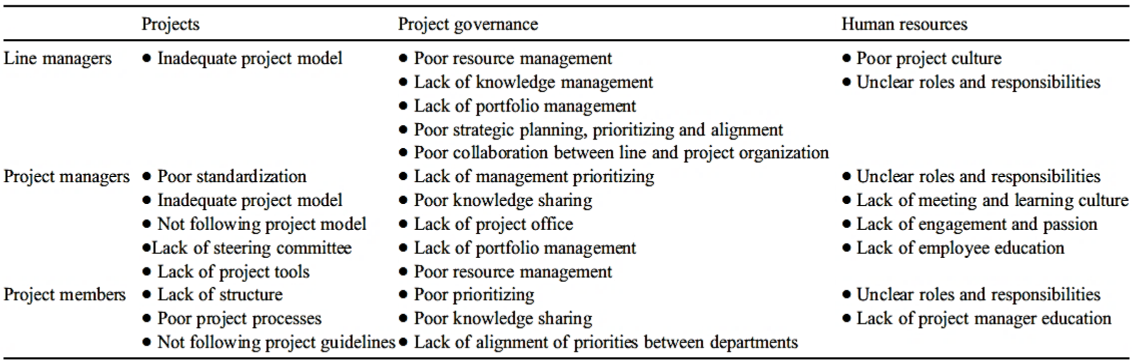
### *3.4.2 Integrated Design in Practice*

Without the ID application, manufacturing companies can face project overruns and increasing cost and quality issues because of lack of information related design, production process and material (Pullan *et al.* 2010). Many manufacturers, such as Rolls-Royce, Hewlett-Packard, Motorola, and General Motors, have successfully adopted an integrated design process, applying all characteristics together (Otto and Wood 2001, Bhuiyan *et al.* 2006, Pullan *et al.* 2010). The benefit derived from such successful applications have led to increased attention to ID in many product design models/approaches in the past (Costa *et al.* 2015). More recently, it has been reported that the adoption of ID in design practice has been significantly reduced (from 69% in 2004 to 49.1% in 2012) (Markham and Lee 2013). This is because many of these efforts have not resulted in perceptible benefits due to the lack of a structured collaborative approach, inaccessibility of information and knowledge, and inability to manage process complexities (Tomiyama *et al.* 2009). In a context of ID between PD and PSD, one survey has revealed that the support from the manufacturing department was still low in comparison with other departments such as marketing and business unit departments during the product design process (Markham and Lee 2013). In the same way, it is also reported that PSD still did not gain much attention from designers currently since there is only 10% of the time during the early design stages that designer focused on production system aspect (Cash *et al.* 2015).

Many studies have identified key effective practices and challenges to support ID implementation to enhance this situation. To effectively apply ID, a company should adopt a formal design process and well-organised information sharing (Peng *et al.* 2014). Rauniar *et al*. (2017) have noted that it is important to spend adequate time for sharing the ID project's objectives and mission, as well as to have clear target trade-off during the early front-end stage. That is because this leads to effective cross-functional teams and efficient ID product outcomes. In addition, ID effectiveness can also be improved through customer and supplier involvement due to information enhancement. In Table 3.6, Sommer *et al*. (2014) have concluded the challenges of implementing ID in industry practice based on projects, project governance, and human resources.

Moreover, another group of ID study has evaluated the implementation of ID characteristics based on different aspects such as ID benefits, ID performance, and design process aspects supporting the realisation of ID.

*Table 3.6 – Challenges in IPD related to each of the three project organisation elements (Sommer et al. 2014).*



| | Projects | Project governance | Human resources |
|---|---|---|---|
| Line managers | • Inadequate project model | • Poor resource management<br>• Lack of knowledge management<br>• Lack of portfolio management<br>• Poor strategic planning, prioritizing and alignment<br>• Poor collaboration between line and project organization | • Poor project culture<br>• Unclear roles and responsibilities |
| Project managers | • Poor standardization<br>• Inadequate project model<br>• Not following project model<br>•Lack of steering committee<br>• Lack of project tools | • Lack of management prioritizing<br>• Poor knowledge sharing<br>• Lack of project office<br>• Lack of portfolio management<br>• Poor resource management | • Unclear roles and responsibilities<br>• Lack of meeting and learning culture<br>• Lack of engagement and passion<br>• Lack of employee education |
| Project members | • Lack of structure<br>• Poor project processes<br>• Not following project guidelines | • Poor prioritizing<br>• Poor knowledge sharing<br>• Lack of alignment of priorities between departments | • Unclear roles and responsibilities<br>• Lack of project manager education |

First, Gerwin and Barrowman (2002) have evaluated each ID characteristic against the two key benefits of design failure reduction and development time reduction. The results are that overlapping processes, specific methods and information sharing can achieve both failure and development time reduction. Regarding another characteristic, cross-functional team/strong collaboration tends to result only in development time reduction.

In addition, Peng *et al*. (2014) studied the effects of ID practices and ID tools on **design collaboration**. The results revealed that all ID practices, such as overlapping phases, cross-functional teams and early engagement of stakeholders did effectively support design collaboration. In a context of ID tool, most of the tools such as CAD, CAPP, simulation modelling, and shared part databases (except email groupware and PDM software) are positively support design collaboration (Barczak *et al.* 2009). In addition, this study also found that collaboration through ID practices are more necessary for the cases that there is **a higher degree of design task interdependence and/or higher design novelty** (higher design newness/information ambiguity). Especially at higher design novelty, ID practice significantly required support from ID tool for interpreting, clarifying, and organizing information.

In an aspect of the **number of product functions**, Ahmad *et al*. (2013) have discovered that when project complexity increases due to higher numbers of product functions, integrated design teams (cross-functional teams) become essential for improving product development. These finding of ID characteristics on different design aspects are concluded in Table 3.7.

*Table 3.7 – Effects of ID characteristics on different design aspects*

| **ID Characteristics** | | **Support to** | | | **Support collaboration different aspect** | | | |
|---|---|---|---|---|---|---|---|---|
| | | **Reduce design failure** | **Reduce development time** | **Design collaboration** | **High task interdependency** | **High novelty** | **Larger product size** | **Higher product functions** |
| **ID Practice** | Overlapping processes | ✓ | ✓ | ✓ | ✓ | ✓ | - | - |
| | Specific method (early application) | ✓ | ✓ | ✓ | ✓ | ✓ | - | - |
| | Cross-function, teaming | ✗ | ✓ | ✓ | ✓ | ✓ | - | ✓ |
| **ID IT Tool** | Information sharing | ✓ | ✓ | ✓ | - | ✓ | ✓ | - |

In a context of ID adoption period, Kong *et al*. (2015) found that the integration of manufacturing considerations too early (marketing and product feasibility) or too late (production development) during product development had negative effects on both speed and cost performance. Therefore, it is highly essential to achieve integration from an early stage, and during the product design phase to gain positive effects which are higher performance related to not only to product development but also to the market. Nevertheless, "*in order to maximise product development performance, managers should work on enhancing manufacturing integration by focusing on the right stages over the entire ID process.*"(Kong *et al.* 2015). This is because the different nature of tasks in different product design processes calls for differing levels of support from manufacturing at different stages.

In conclusion, existing ID approaches and tools were proposed and implemented to support information and knowledge sharing between individual design processes, in place of generating a combined process. In any case, integrated design concepts are typically unidirectional approaches mainly assisting the product designers to consider manufacturability (Stoffels and Vielhaber 2016). In addition, the research to date has tended to focus on the last three characteristics of ID rather than the integrated design process area. A common observation in most of these studies is that integrated design should not mainly be utilised to meet a narrow target such as cost and time reduction. Significantly, with regard to current challenges, integrated design concepts must respond to conventional benefits and explore wider potential benefits such as improved resource efficiency (Haapala *et al.* 2013, Sheldrick and Rahimifard 2013). This highlights that the design of production systems is often the 'outcome of decided product design,' which typically limits the potential benefits of a truly integrated and simultaneous approach for designing product and its production system.

## 3.5 CHAPTER SUMMARY

In this chapter, a literature review of PD, PSD and ID were undertaken to provide basic knowledge about how product and production system design is processed and how they interact with each other. However, this review concluded that most of these proposed ID approaches were not often adopted due to being difficult to implement. This suggests that future approaches should give more consideration to the application and implementation aspects of ID. Equally important, many studies have emphasised a need to update the existing approach to respond to contemporary challenges such as sustainability requirements.  In order to understand if existing sustainable design practice meets the requirement of integrating product and production system design, the next provides a detailed review of contemporary SD practices.

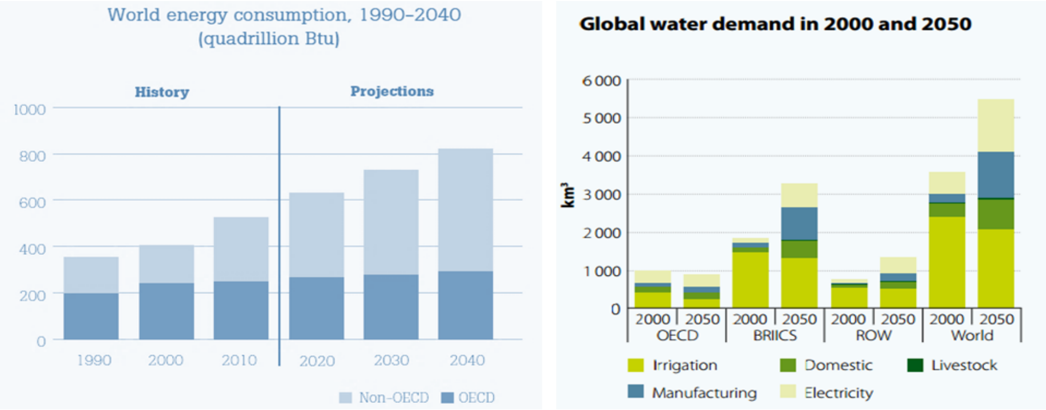
# CHAPTER 4 SUSTAINABLE DESIGN

## 4.1 INTRODUCTION

The previous chapter addressed design challenges, such as shorter development time and product quality, which demand the application of more efficient and closely integrated design. Recently, sustainability, which is one of the unavoidable challenges for the industry, was also highlighted as achievable through integration and collaboration during the design phase. This chapter therefore explores the current state of sustainable design in manufacturing application. The first section presents the key drivers of sustainability considerations. Then the two following sections provide the state-of-the-art of sustainable design for product and production systems.

## 4.2 DRIVERS OF SUSTAINABLE DESIGN

Environmental awareness had emerged at least since the 1980s when the hole in the ozone layer and global warming were discovered (Sheldrick and Rahimifard 2013). Based on the forecast of increasing population by 2050, this issue will consequently become more crucial (Foresight 2013). Specifically, the requirements of resource consumption dramatically increase, and resource scarcity, rising material costs, climate change, and other issues will be more critical in the near future (see Figure 4.1). Accordingly, the environmental attention from various sectors will drive the future of PD and PSD as highlighted in the following subsections.



Note: BRIICS (Brazil, Russia, India, Indonesia, Chaina, South Africa); OECD ( Organisation for Economic Co-operation and Development); ROW (Rest of the world)

*Figure 4.1- Projection of World energy (Left) and water (Right) consumption* (Tennant 2013, WWAP 2015)

### *4.2.1 Legislation, Standards and Governmental Driver*

In 1306, the first environmental legislation in the UK was an ordinance limiting coal burning to reduce air pollution in London. Since then, air pollution, industrial waste, water emission and import-export-storage of prescribed or radioactive substances have been controlled by the Environmental Protection Act (Government of UK 1990). After that, with the aim to improve effectiveness, an environmental agency was established to monitor environmental issues in the UK through Integrated Pollution Control (IPC), which is the integration of all existing environmental controls, as shown in Figure 4.2 (HM Government 1995). In the EU, the Waste from Electrical and Electronic Equipment (WEEE) directive and the End-of-Life Vehicles (ELVs) directive were established with the aim to build producer responsibilities. WEEE specifies that producers need to control the reuse, recycling and recovery of their electrical and electronic wastes (European Parliament 2003). ELVs was applied to enforce automobile manufacturers to recover 95% of their end-of-life vehicles, and a minimum of 85% of component parts need to be reusable or recyclable (European Parliament and Council of the European Union 2000). Under this legislation, manufacturing companies cannot avoid including environmental considerations during development of their production systems and, especially, at product design. Furthermore, to mitigate these environmental issues in the long term, manufacturers are expected to achieve sustainable design targets and goals (for both product and production system) in a three-phase plan which has been suggested, as in Figure 4.3 (Foresight 2013).

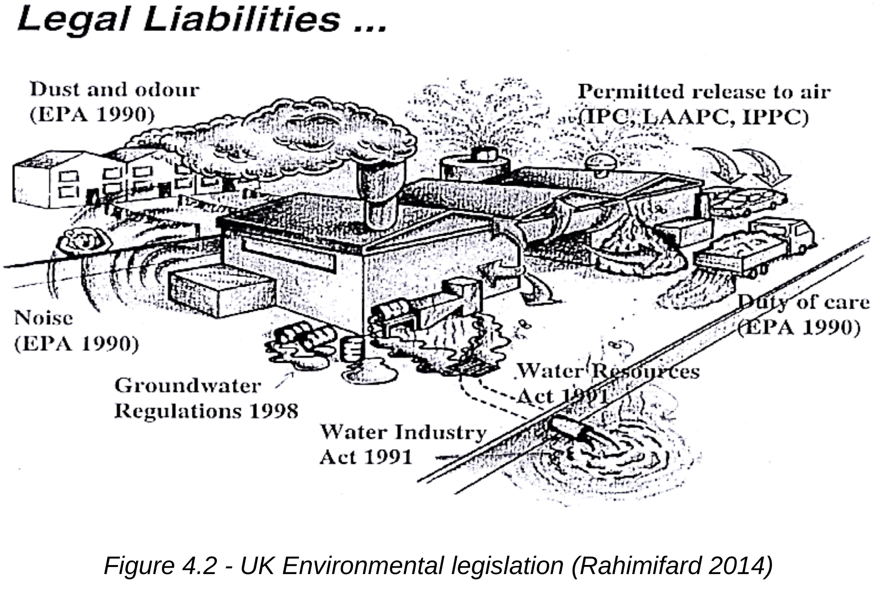


*Figure 4.2 - UK Environmental legislation (Rahimifard 2014)*

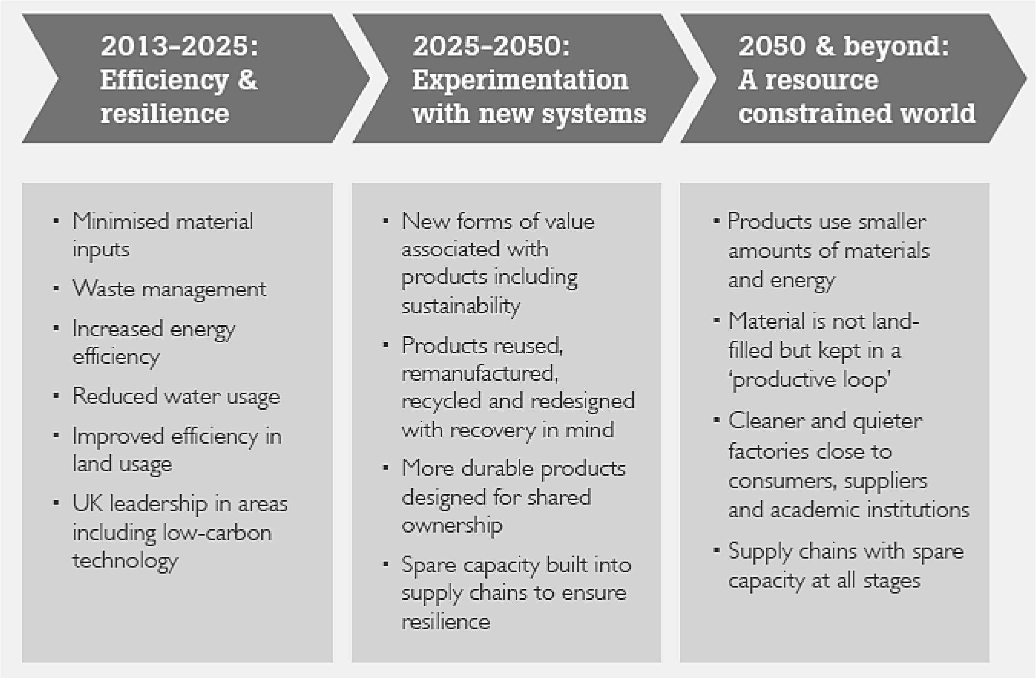


*Figure 4.3 - Three phases in the shift to sustainable product and production system (Foresight 2013)*

### *4.2.2 Market and Consumer Driver*

The higher pressure of environmental issues and resource requirements has raised environmental consciousness in consumers in the past decade (Sheldrick and Rahimifard 2013). One consumer survey revealed that 75% of Europeans were willing to purchase environmentally friendly products even if the price is slightly higher (European Commission 2014). In the same way, the more than 50% of global respondents who are willing to pay more for green products *"are influenced by key sustainability factors, such as a product being made from fresh, natural and/or organic ingredients (69%), a company is environmentally friendly (58%), and company is known for its commitment to social value (56%)"* (Nielsen 2015). Additionally, it has been forecasted that sustainability will strongly influence consumer goods markets in the future. This is presented in four possible scenarios of sustainable consumption, based on the variation in attitudes of society and its leaders as illustrated in Figure 4.4 (Bennie *et al.* 2011). Therefore, the manufacturer should be able to cope with this increasing trend of the sustainable product by effective implementation of sustainable design.

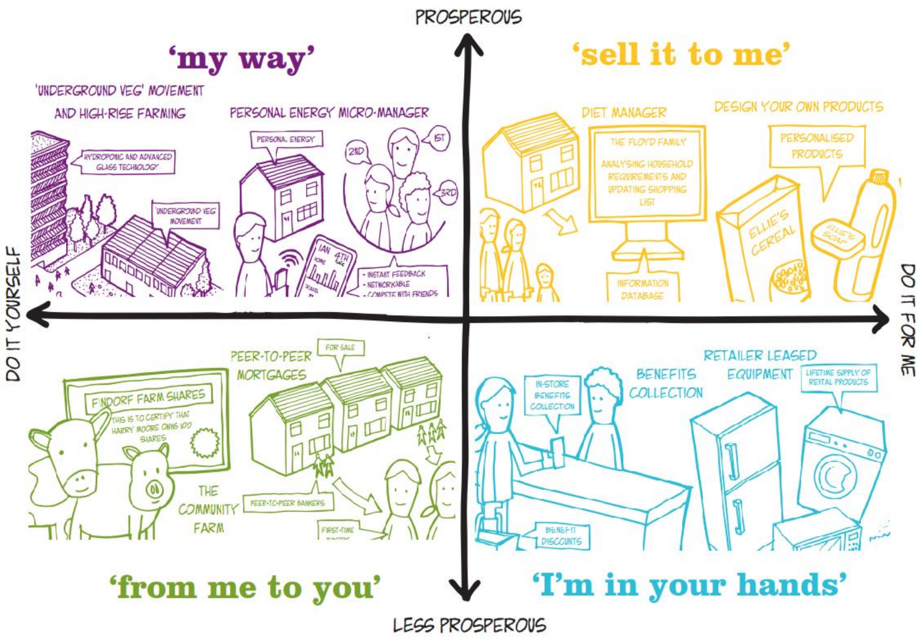


*Figure 4.4 – Four scenarios for future consumers* (Bennie *et al.* 2011).

### *4.2.3 Business Driver*

In light of these drivers from the consumer and government, it is obvious that the consideration of environmental issues has become one of the key success factors for manufacturing businesses. In this past decade, several manufacturing businesses have started to consider the environmental aspect along with their economic mindset. For instance, at British Sugar, the production process has been redesigned to reuse resources such as water, heat, and electricity, transferring them from one process to another. For instance, bagasse, which is waste from sugar production, was processed and sold as an animal feed product. In addition, heat emission from the evaporation process was further used for tomato farming, as shown in Figure 4.5. Furthermore, the company has also supported its neighbours by sharing the excess electricity of the factory to support the electrical grid in the local area (LimeX 2014). It can be seen that the adoption of a sustainable strategy provided numerous advantages in terms of natural resources, the neighbouring society, and business revenue. Hence, manufacturers who more quickly satisfy the present-day needs of environmental sustainability will secure their existence and become more competitive in business.

Given this increasing environmental awareness, a sustainable strategy is not only the best option to satisfy the increasing demands of consumers, but it is now a requirement to implement in manufacturing businesses. In fact, many manufacturers nowadays do realise the importance of

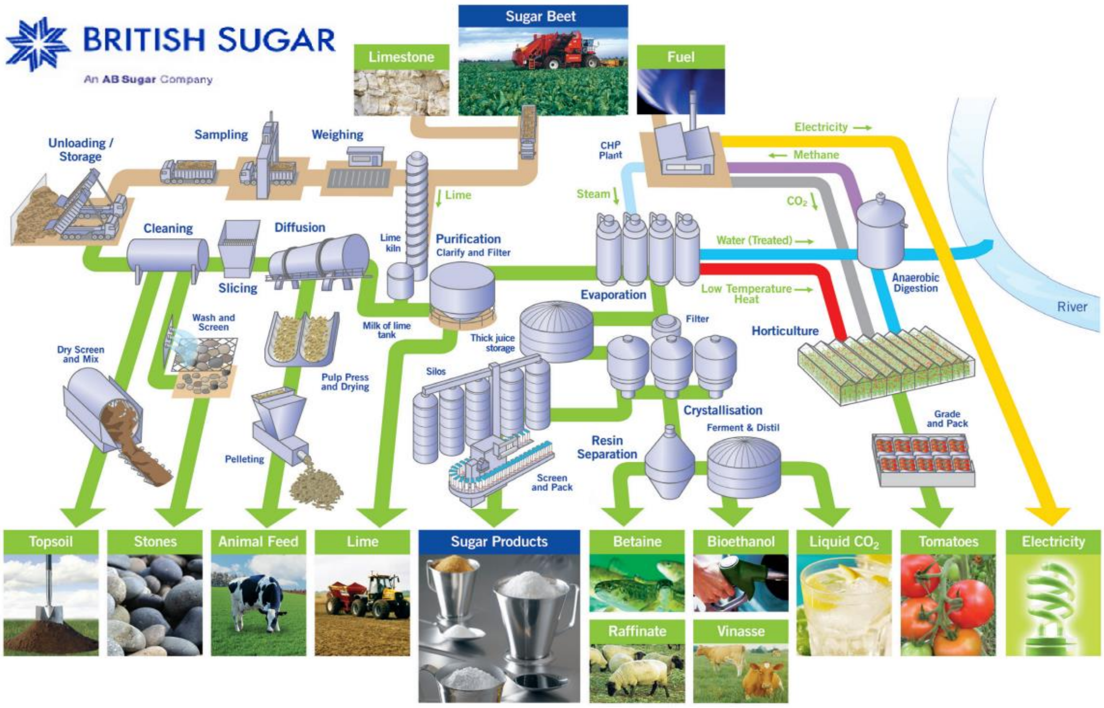


*Figure 4.5 – British Sugar factory operation - an example of sustainable manufacturing* (LimeX 2014)

environmental improvement (Giddings *et al.* 2002, Gunasekaran and Spalanzani 2012, Deutz *et al.* 2013). Nevertheless, they are now faced with difficulties in implementing sustainability with their products and production system. Based on the potential for early adoption of sustainability during design, the sustainable design of the product and production system is explored in the following section.

## 4.3 SUSTAINABLE PRODUCT DESIGN

Even though the term ‘sustainability’ has just emerged in recent decades, it has gained much attention due to the long-term development of environmental consciousness. Also, it is well-known that the key to success in sustainability is to embed and implement sustainable strategies since the early stages of product design and development (Ullman 2003, Kara *et al.* 2005, Luttropp and Lagerstedt 2006, Bovea and Pérez-Belis 2012, Hallstedt *et al.* 2013, Red *et al.* 2013). Otto and Wood (2001) also highlight that, similar to production cost, 80% of the environmental impact of a product is settled after 20% of the product design is completed.  In this light, this section explores sustainable product design, including the concept, theoretical methodologies, and industrial practice.

### *4.3.1 An Overview of Sustainable Product Design*

Sustainable Design or design for sustainability (SD), is established to design products focusing on the ecological aspect, the social aspect and the economic aspect. The objective is to design a product which functions effectively and has a low environmental impact and a positive social impact, as reflected in usability and responsible use (Bhamra and Lofthouse 2007). SD can be considered as the extension of 'design for environment (DfE) or Eco-design' with regard to the definitions in Table 4.1 (Spangenberg *et al.* 2010).

Eco-Design/DfE is widely recognised as a design concept that integrates environmental considerations into the design process in order to create a more environmentally friendly product (Bhamra and Lofthouse 2007). This concept entails applying various approaches under the concept of green design, which commonly focuses on a single issue related to environmental improvements, such as design for recycling, design for the life cycle, design for longevity, and design for disassembly (Marcelino-Sádaba *et al.* 2015). For example, Luttropp and Lagerstedt (2006) proposed the Ten Golden Rules to help designers to simply design an environmentally friendly product based on ten key considerations of the product life cycle (see Figure 4.6).

Reflecting the long-term development of the eco-design concept, this is why most sustainable design methods were developed: to design a sustainable product with an ecological concentration such as a use of less energy, fewer resources or more environmentally appropriate materials, or release of less harmful waste and emissions (Ryan *et al.* 1992, Ramani *et al.* 2010, Bovea and Pérez-Belis 2012, Sheldrick and Rahimifard 2013). Nevertheless, some approaches

*Table 4.1 - Differentiation of environmental design philosophies (Bhamra and Lofthouse 2007)*

| **Green Design** | **Green design focuses on single issues, for example, the inclusion of recycled or recyclable plastic, or consideration of energy consumption** |
|---|---|
| **Eco-design** | Environmental considerations are considered at each stage of the design process |
| **Design for sustainability** | Design that considers the environmental (for example resource use, end of life impact) and the social impact of a product (for example usability, responsible use) |
| **Sustainability** | Sustainability is considered to be more of a direction than a destination that we will actually reach |

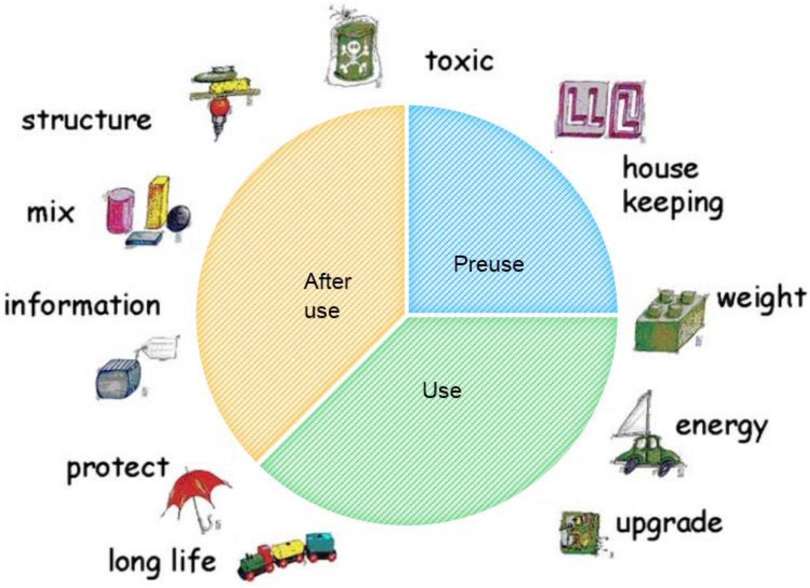


*Figure 4.6 - The Ten Golden Rules are organized according to the life cycle of a product. Each rule is attached to a picture associated with the essence of the respective rules (Luttropp and Lagerstedt 2006)*

have covered all sustainable aspects. For instance, the five elements of the Cyclic-Solar-Safe Principle, which are Cyclic, Solar, Safe, Efficient, and Social, were generated for measuring the environmental aspect and protecting human rights in both the production and the use phases of products (Datchefski 2001). Other examples are the cradle-to-cradle of the McDonough Braungart Principle, the Walker Principle and a strategic sustainability perspective (Hallstedt *et al.* 2013).

Even though the concept of sustainable design has extensively grown in the context of research and industrial practices in the past decade, it has still required further development, in many aspects (see Figure 4.7) such as the social one, as well as improvement in environmental implementation (Spangenberg *et al.* 2010, Hallstedt *et al.* 2013, Marcelino-Sádaba *et al.* 2015). Therefore, the next section provides a summary of current practices in sustainable product design.

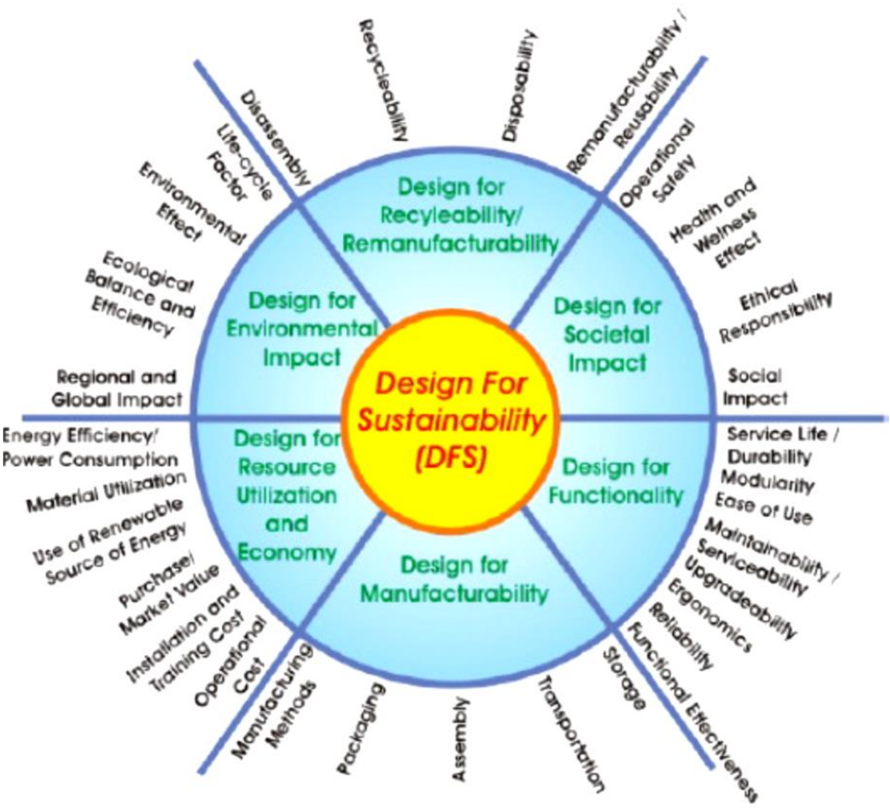


*Figure 4.7 - Key considerations of Design for Sustainability (DfS) (Lyngaas 2014)*

### 4.3.2 Sustainable Product Design in Practice

After exploring the concept of sustainable product design, this section aims to investigate sustainable product design in practice based on the implementation challenges of sustainable tools and methods to clarify the further improvement required.

A large volume of research has attempted to support sustainability applications through proposed sustainable design tools and methods. These have been developed for application at different design stages. For the early stage of concept design, the Design for Environment Matrix and Simplified/Streamlined Life Cycle Assessment tools have been developed to support ecological decisions made in material or concept selections (Bovea and Pérez-Belis 2012, Zhang *et al.* 2017). With a similar purpose, some eco-design tools (see Figure 4.8) which have been summarised by Bovea and Pérez-Belis (2012) were adapted from traditional design tools such as QFD, Failure Mode Effect Analysis, and Matrix design to ease implementation. During the testing and refinement stage, designers can define where a designed product needs ecological improvement using Risk Analysis, Total Cost Assessment or life cycle assessment software tools, such as SimaPro and Gabi (ISO 2006, Sheldrick and Rahimifard 2013).

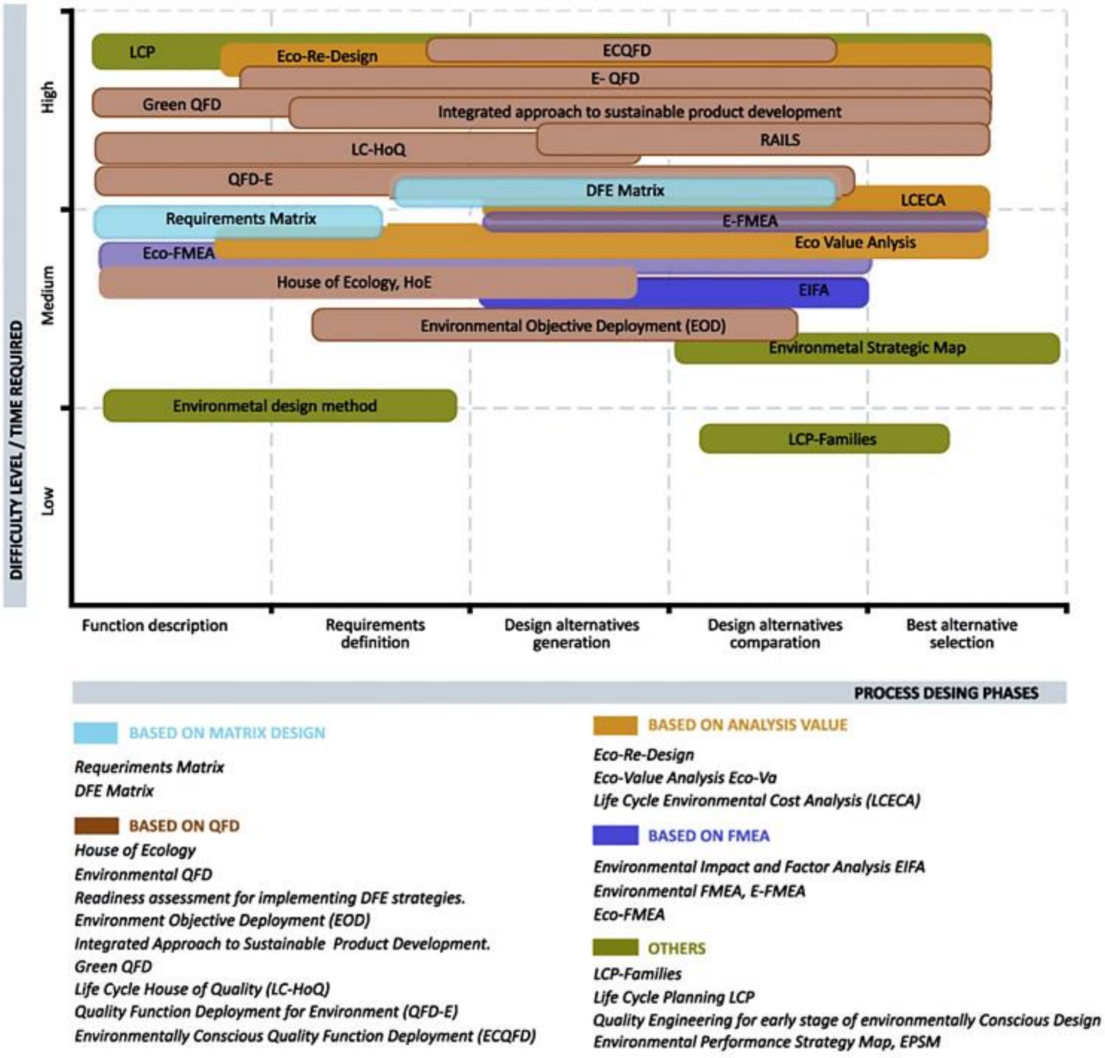


*Figure 4.8 - Classification of tools integrating environmental requirements into the design process (Bovea and Pérez-Belis 2012)*

Apart from these product-focused methods, a process-focused eco-design approach such as the Eco-design Maturity Model and a process-oriented performance indicator has been introduced to support and improve the integration of eco-design into product development and related processes (Rodrigues *et al.* 2017).

Although eco-design from an academic perspective has been progressively developed, one survey reported that sustainability was applied as policy, seriously considered or truly implemented in 50%, 20% and 10% of companies, respectively (Markham and Lee 2013). In addition, sustainability strategy was applied more by the best practice and large companies which perform design through a formal and structured product design process (Gunasekaran and Spalanzani 2012). Hence, it has been questioned why the proposed approaches were often not successfully adopted in practice (Boks and McAloone 2009, Short *et al.* 2012, Pigosso *et al.* 2013).

Several studies have shown that this is because most of these tools are complex, lack implementation guidance and require specific training, a large amount of data, and particularly additional time and effort during the product development process, which is time-limited (Bovea and Pérez-Belis 2012, Rossi *et al.* 2016). Besides, Sheldrick and Rahimifard (2013) have underlined that most of these methods and tools were lately implemented sustainability; hence, they provide only incremental benefits, instead of radical benefits from the application.

Although the significance of sustainable development was realised (Short *et al.* 2012), product designers can easily select familiar solutions that might be not environmental friendly, owing to an inability to see the impact of eco-design decisions on the manufacturing system (Giddings *et al.* 2002, Deutz *et al.* 2013).This was also because of a lack of information, concerning, for instance, the resource consumption of manufacturing processes, led to unsuccessful eco-design applications (Dekoninck *et al.* 2016). Therefore, to maximise sustainable development, several researchers recommended that the design of product and production systems should be considered simultaneously (Haapala *et al.* 2013, Ghisellini *et al.* 2016).

The requirement of integration between PD and PSD was also agreed by Gagnon *et al*. (2012) who has highlighted that when *"sustainability issues [are] addressed, it will likely prove more efficient to do so at the beginning of the design… Such an approach is coherent with the early integration of manufacturing or assembly considerations in concurrent engineering"* In order to achieve this, a company should consider modifying conventional approaches and organising a multifunctional team (from staff with different skills and knowledge) to increase the understanding of sustainability issues and include all possible solutions (Le Pochat *et al.* 2007, Rossi *et al.* 2016)

## 4.4 SUSTAINABLE PRODUCTION SYSTEM DESIGN

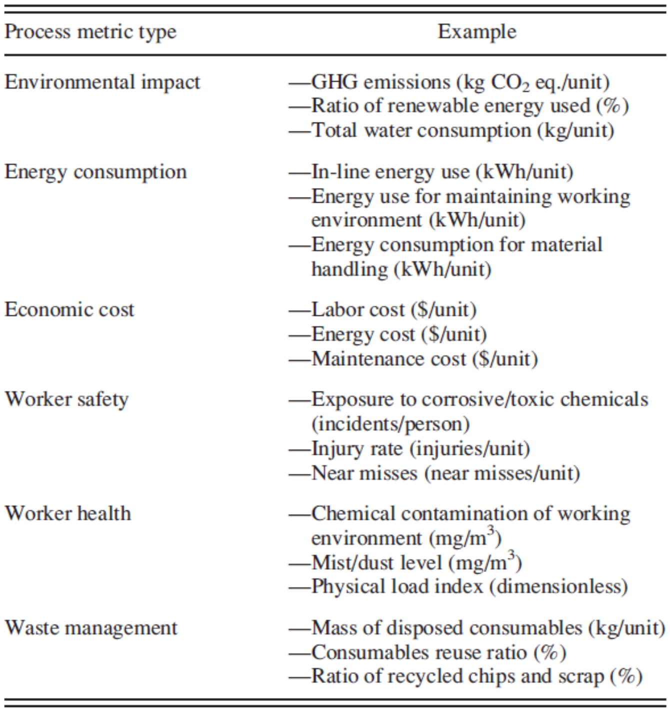
There is a great deal of research and industrial practice exploring how to make manufacturing systems more sustainable. This covers a range of subjects, from improving the efficiency of manufacturing processes and factory operations through to supply chain management and business operations (Jawahir and Dillon Jr 2007, Ramani *et al.* 2010, Gunasekaran and Spalanzani 2012, Haapala *et al.* 2013). Shifting to a more effective proactive approach, the early consideration of sustainability at the production system design phase is required to maximise the utilisation of natural resources, reduce emissions and thus minimise resource requirements.

However, there is a lack of proactive methods specifically at this phase (Alayón *et al*. 2017). This is because it is very expensive to overhaul entire factories, and very infrequent that a company may design a ‘sustainable’ production system from scratch. Instead, it is more common that they would make changes and upgrades to the existing infrastructure, as this is less disruptive and requires less investment. Presented in this section are a number of approaches for managing, redesigning, or changing the existing production system into a sustainable one.

### *4.4.1 An Overview of Sustainable Production System Design*

To adopt a sustainable strategy, manufacturers generally start with a sustainable evaluation of their systems, considering the input (material and energy) and output (waste, as well as land, water and air emissions) of the system (Haapala *et al*. 2013). This supports the identification of “hotspots” where the largest challenges and opportunities are and help target design improvement activities appropriately. To effectively evaluate the sustainability of a production system, a sustainable measurement metric is required. Over the long period of environmental awareness, the number of existing environmental metrics is significantly higher than the number of social metrics, as the latter is difficult to quantify and in the initial phases (Jørgensen *et al*. 2008). However, some studies have proposed quantified units for both social and environmental measurement (see Table 4.2).

*Table 4.2 - Quantitative measurement of social and environmental evaluation (Lu et al. 2010)*



| Process metric type | Example |
|---|---|
| Environmental impact | —GHG emissions (kg $CO_2$ eq./unit)<br>—Ratio of renewable energy used (%)<br>—Total water consumption (kg/unit) |
| Energy consumption | —In-line energy use (kWh/unit)<br>—Energy use for maintaining working environment (kWh/unit)<br>—Energy consumption for material handling (kWh/unit) |
| Economic cost | —Labor cost ($/unit)<br>—Energy cost ($/unit)<br>—Maintenance cost ($/unit) |
| Worker safety | —Exposure to corrosive/toxic chemicals (incidents/person)<br>—Injury rate (injuries/unit)<br>—Near misses (near misses/unit) |
| Worker health | —Chemical contamination of working environment ($mg/m^3$)<br>—Mist/dust level ($mg/m^3$)<br>—Physical load index (dimensionless) |
| Waste management | —Mass of disposed consumables (kg/unit)<br>—Consumables reuse ratio (%)<br>—Ratio of recycled chips and scrap (%) |

With these measurement metrics, many sustainable methods and tools are established for evaluating and improving sustainability across all levels within the factory, including machine tools, process, and the whole manufacturing system (see Table 4.3). These SPSD methods were proposed to support different levels of the application as follows.

#### *4.4.1.1 Sustainable Production System Design Methods for system level*

Environmental Management System (EMS) is an integrated framework for managing, controlling and monitoring the environmental impact of process and operation based on the requirements of ISO 14001 and ISO 14004 standards (ISO 2015, 2016) as well as the Eco-Management and Audit Scheme (European Council 2009). The implementation steps of the Plan Do Check Action key in EMS can identify the company's activities and their environmental impact, arrange environmental policy based on involved legislation, set improvement objectives, and issue control documents for all processes and related activities in order to conduct environmental audits and set future improvement plans. (ISO 2015, 2016). The implementation of EMS can enable one to focus on continuous improvement on environmental issues (Haapala *et al.* 2013).

*Table 4.3 - Sustainable production methods and tools*

| Category | Description | Example methods |
|---|---|---|
| **System Assessment and Evaluation** | These methods focus on measuring input and output in both the process and system level for supporting the environmental improvement | Growth sustainability based on lean manufacturing (Miller *et al.* 2010) and energy-cost efficiency modelling (Anderberg *et al.* 2010) |
| **Simulation modelling** | Quantitative Methodologies for supporting process planning, scheduling, line balancing in environmental practice | Simulation style Competence-based and Technology-Enhanced Learning (TEL) environments |
| **Install sustainable process** | An additional process such as remanufacturing, recycling and disassembly process is adopted in the production line | Material Requirement Planning for the sustainable process, integer programming (IP)-based algorithm, and Mixed Integer Linear Programming based aggregate production planning model |
| **Strategy/Guidelines** | The tools can provide broad requirements in sustainable practice | 3R, 6R strategy, Eighteen principles (Monozukuri) |
| **Framework** | The suggestion of common steps to adopt sustainability in the manufacturing system | Environmental Management System (EMS) |

In addition, "Monozukuri" was introduced as the "Eighteen principles" for being sustainable, focusing on a rule-based approach. This set of principles guides success in sustainability, such as the need for management's attention, embedding in the culture of the company, and adopting green technologies (Ranky 2010). Moreover, a five-step framework for sustainable production system design which was adapted from manufacturing system design decomposition was introduced to redesign the current system through the collection of life cycle requirement and assessment design solutions (Herrmann *et al.* 2009).

Other methodologies, including the modelling of waste and energy optimisation, are developed to analyse, evaluate, and manage environmental issues at the system level (Bi 2011). These types of models have a similar concept with environmental evaluation but apply in the broader view at the system level. Specifically, the models work by collecting data on waste, energy and costs, then manage energy resources based on manufacturer information to reduce energy usage and waste impact; examples are growth sustainability based on lean manufacturing, and energy-cost efficiency modelling (Anderberg *et al.* 2010). Similarly, to evaluate the environmental impact of a production process, several techniques such as Life Cycle Assessment and Resource and Environmental Profile Analysis are often applied in practice (Kalakul *et al.* 2014).

Sustainability was also addressed in production system simulation modelling, such as in simulation style competence-based, Technology-Enhanced Learning environments and in the SIMTER environmental assessment (Heilala *et al.* 2008, Cerinšek and Abbas 2013, Lee *et al.* 2014). This research can support process selection, facilities and layout design, product planning and scheduling, as depicted in **Error! Reference source not found.**.

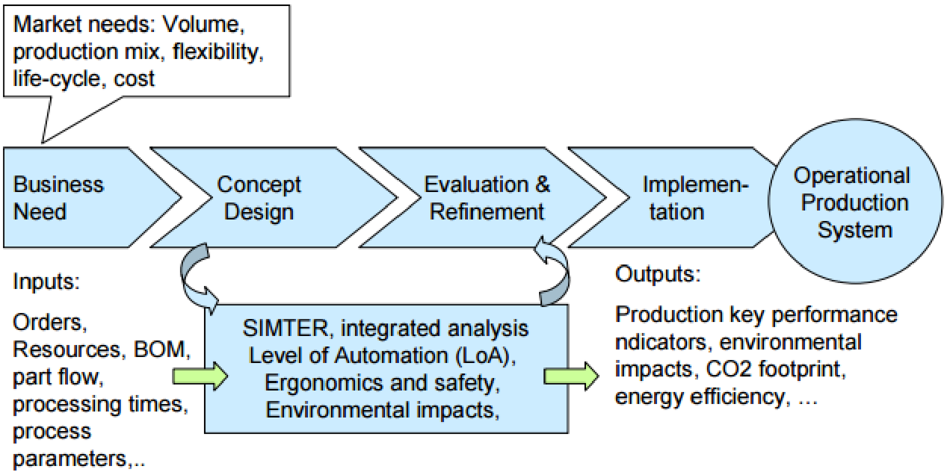


*Figure 4.9 - The SIMTER environmental assessment tool for sustainable manufacturing system design (Heilala et al. 2008)*

#### ***4.4.1.2 Sustainable Production System Design Methods for machine tool and process level***

It is highly significant to select machine tools and processes which can satisfy the production function, require fewer resources (water, material, energy) and produce lower levels of waste and pollution (e.g. gas emission, carbon emission). The main application of sustainable considerations at the process level can be grouped into two steps, which are process evaluation and process improvement. For instance, Jawahir and Dillon Jr (2007) proposed six main aspects: environmental friendliness, machining cost, power consumption, waste management, operational safety, and personal health for sustainable evaluation in machine and process. For the current environmental enhancement, high-performance fabricate technologies like the laser-based manufacturing process and micro-factory retailing also provide benefits in sustainability due to optimum material utilisation (Williams 2006). Bi *et al.* (2015) redesigned reconfigurable machine tools based on the 6R strategy (reduce, reuse, recycling, remanufacturing, redesigning, recovering) by considering their usage from the pre-manufacturing, manufacturing, use to post-use phases. As a result, the adoption of 6R in reconfiguring machines reduced the raw material requirements by reusing existing components, improving the capabilities and flexibility of machine tools and resulting in cost reductions (Ijomah *et al.* 2007). Moreover, many production processes such as metal manufacturing and chemical manufacturing have been redesigned; these are presented in Table 4.4 (Haapala *et al.* 2013).

#### ***4.4.1.3 New sustainable production processes***

In addition to the redesigned processes, several sustainable processes were developed and adopted in sustainable production systems. These can further the boundaries of traditional production systems and support ecological activities such as product take back, remanufacturing, reuse and recycling. These specialist operations are becoming more frequent and widespread with the increasing trend in service-based businesses and circular economy initiatives.

The remanufacturing process, which consists of refurbishing disassembled parts to have a similar condition to a new one with a shorter lead-time, provides many benefits to manufacturing systems such as automobile manufacturing (Ilgin and Gupta 2010). Some well-known remanufacturing cases are the single-use cameras of Kodak and Fuji film, photocopiers of Fuji Xerox, and Caterpillar machines (APSRG 2014). Many methods were researched at each step of the remanufacturing process, starting from forecasting models for calculating the amount (Marx-Gómez *et al.* 2002) and lifetime (Linton *et al.* 2005) of the product.

*Table 4.4 - Sustainable improvement of different manufacturing processes adapted from (Haapala et al. 2013)*

| **Manufacturing process** | **Main environmental impacts** | **The improvement areas** |
|---|---|---|
| **Metal manufacturing** | | |
| • ***Casting*** | • Hazardous air pollution, water emission, and solid waste in sand casting and cooling processes | • Development of sand mould and thermal management |
| • ***Forming*** | • Co₂ emission, resource use | • Net-shape forging and reconfigurable dies |
| • ***Machining & grinding*** | • Health and environmental concerns from chemicals and lubricants in process | • Use of alternative fluids such as liquid nitrogen |
| • ***Cleaning & finishing*** | • Water pollution from toxic chemicals (cadmium, chromium), high energy use in thermal surface finishing | • Applying a low-energy process, developing close-loop finishing process |
| **Chemical process** | | |
| • ***Solvents*** | • Improper disposal of solvent use such as supercritical co₂, gas-expand liquid | • Applying alternative chemicals which provide a lower impact |
| • ***Lubricants*** | • Resource scarcity from using a petroleum-based lubricant | • Replacement of bio-based lubricants |
| • ***Hydraulic fluids*** | • The largest energy consumption in plastic production | • Operation improvement |

Then, product planning methodologies are requested to manage the material requirements between new parts and disassembled parts by Material Requirement Planning (MRP) (Ferrer and Whybark 2001), Integer Programming (IP)-based algorithms (Sarkis 2001), and the MILP-based aggregate production planning model (Xanthopoulos and Iakovou 2009), which broadly determine the optimal number of products for collection, disassembly, remanufacturing, storage, back order and disposal. Furthermore, much research in remanufacturing focuses on production scheduling, capacity planning and inventory management, including deterministic models, stochastic models, and cost and value evaluation, in order to improve the implementation of remanufacturing systems (Kurilova-Palisaitiene *et al.* 2018).

Reuse and recycling of consumer goods can effectively reduce resource extraction. For instance, one ton of recycled pulp paper can save almost twenty trees, three square meters of landfill, and water and energy use in the material extraction phase (Garner 2002). To adopt a repair and upgrade, remanufacturing and recovery strategy, products should be easily separated and disassembled into components(Moore *et al.* 2001, Ilgin and Gupta 2010).

Disassembly, defined as the systematic disjoining of assembled components and sub-assembled parts, is also worth noting (Moore *et al.* 2001). The disassembly process is a very significant one in material and product recovery before the application of recycling or remanufacturing and is widely developed in scheduling, sequencing, line balancing, and automation. However, since the disassembly process is present time-consuming, several researchers have proposed methods to determine disassembly time in order to identify and improve the design of product parts which are difficult to disassembly (Vanegas *et al.* 2018).

### *4.4.2 Sustainable Production System Design in Practice*

As mentioned in the previous section, most of the existing publications were in the area of system improvement rather than addressing proactive approaches or the design of sustainable systems during the design stage (see Figure 4.10) (Ramani *et al.* 2010, Bi *et al.* 2015). Similarly, it has been reported that most industry practice also takes a reactive approach, to comply with regulatory requirements, market pressure, or technology advancement, whilst the proactive actions were applied in business competition (Sáez-Martínez *et al.* 2016, Alayón *et al.* 2017). Besides this, a reactive approach was more likely to be adopted by SME companies, while a proactive approach was commonly applied by larger ones (Singh *et al.* 2014).

Therefore, various researchers have highlighted the need to consider sustainability at the design stage, especially an integrated consideration of product and production system design (Ramani *et al.* 2010, Zaman 2015, Esmaeilian *et al.* 2016, Gbededo *et al.* 2018),

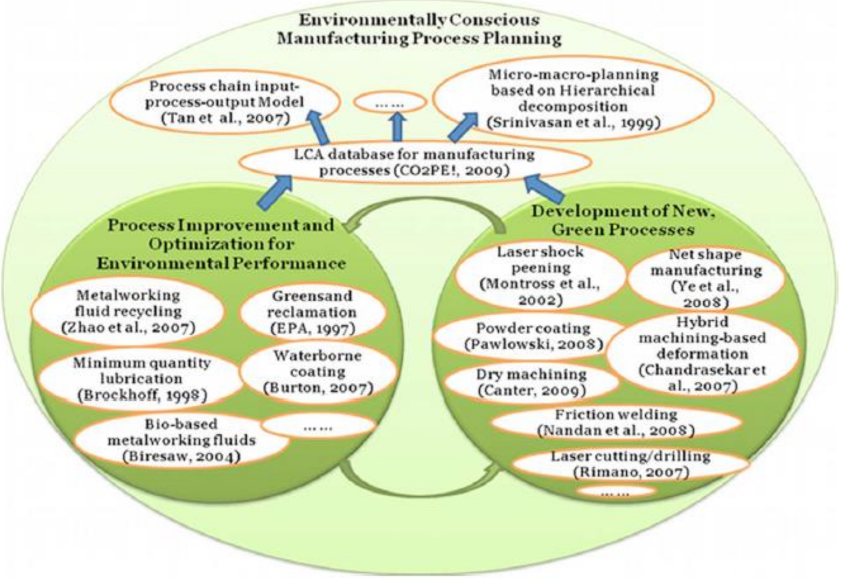


*Figure 4.10 - Sustainable manufacturing research map (Ramani et al. 2010)*

because *"a single focus on designing or re-designing a product for environmental performance without considering the effects of the design on the production process may result in an ineffective decision for the design of a sustainable product"* (Gbededo *et al.* 2018)

It was also recommended that this environmentally sustainable consideration of a product and production system should be fulfilled through the development of:

i. New models, frameworks, metrics, and techniques to transform systems (Molamohamadi and Ismail 2013, Zaman 2015).
ii. Collaborative design through product-process cross-functional integration (Jawahir *et al.* 2013)
iii. Methods to assess the sustainability of the design of a product and its production system (Gbededo *et al.* 2018)
iv. Training to improve knowledge of sustainability for employees and related persons (Jayal *et al.* 2010, Alayón *et al.* 2017)
v. Data support for product-process design, evaluation, selection, and planning, which can be provided through new information technologies, e.g. data-enable technologies (Bi 2011, Esmaeilian *et al.* 2016). For instance, Ramani *et al.* (2010) developed sustainability knowledge into computer-aided process planning (CAPP), which normally focuses on product efficiency, cost and product quality.

In addition to these, in a research context, the majority of sustainable publications were heavily concentrated on the energy aspect, while a small number studies considered other aspects such as material, waste and water efficiency (Esmaeilian *et al.* 2016, Alayón *et al.* 2017, Moldavska and Welo 2017, Gbededo *et al.* 2018). Therefore, the development of design solutions should cover all environmental aspects.

## 4.5 CHAPTER SUMMARY

In this chapter, the requirement of the simultaneous design of P&PS was identified through the increasing design challenges, especially the present need for environmental sustainability. With the environmental pressures from different drivers taken into account, the possibility of collaborative design, assessment, and the creation of sustainable product and production systems was raised in the context of both sustainable product and sustainable production system studies.

In this chapter, the key driver for sustainability consideration in manufacturing application have been identified, and the current practices in Sustainable Design (SD) are presented. This has highlighted that current sustainable design methods are unable to deal with interaction and interrelation between design decision in PD and PSD. Thus, this research has proposed a concurrent approach to design P&PS to support a seamless approach to consider sustainability challenges at an early stage of P&PS design. The next chapter focuses on the integrated design approaches more relevant to the scope of this thesis.

# CHAPTER 5 A REVIEW OF THE MOST RELEVANT RESEARCH IN THE INTEGRATED DESIGN OF PRODUCT AND PRODUCTION SYSTEM

## 5.1 INTRODUCTION

The literature review in Chapters 3 and 4 has highlighted the requirements for the integration of product and production system design. This chapter scrutinises the existing approaches that have been proposed to consider the integrated design of P&PS from various aspects, including environmental sustainability. This is undertaken in order to identify the specific research gaps. This chapter provides an overview of the previous research most relevant to the scope of the work reported in this thesis. The initial section presented a summary of interrelation and interaction requirement between P&PS design processes, and the later sections outline how these requirements are adopted by the recent publications for integration of P&PS design processes. Lastly, this also underlines an evolutionary path to sustainable co-design of product and production system.

## 5.2 INTERRELATION AND INTERACTION BETWEEN P&PS DESIGN PROCESSES

Based on the highlighted need of sustainable integrated design, this section aims to delineate the current state of integration between the design processes of product and production system (P&PS) in order to identify how a manufacturer can move forward from an existing design process to a single co-design process. To complete this, the current integration between design processes of product and production system is investigated through the interrelation and interaction of sample design processes of product and production system, which are modelled using IDEF0 and presented in Appendix I and II. Therefore, the following sub-sections present interrelation and interaction between P&PS design processes and the challenge of integrated design in supporting sustainability.

### *5.2.1 Interrelation Between P&PS Design Processes*

An interrelation (or interdependency) is the term used to identify the relationship between two design tasks or activities subject to the required information in task execution. The relationship between two tasks can be classified as follows (Arundachawat *et al.* 2009):

#### *5.2.1.1 Independent relationship*

This is when two tasks require no information from one another to be carried out. When applying integrated design, these tasks can be freely undertaken in a completely overlapping/parallel pattern.

#### *5.2.1.2 Dependent relationship*

This is when a task requires information/data from a preceding task. Hence, these two tasks are processed in a sequential pattern. When applying integrated design, this pair of dependent tasks can partially overlap through the early sharing of preliminary information.

#### *5.2.1.3 Interdependent relationship*

This is when two tasks require information exchange from each other and any changes to one task directly cause reconsideration (rework) of another. These interdependent tasks can be arranged to overlap partially at the beginning, and subsequently information and decisions made by each task are unidirectionally transferred backwards-and-forwards until final decisions are agreed.

Due to the considerable focus on reduction of development time, a completely overlapping/parallel pattern of tasks in independent relationships is often desirable (Gerwin and Barrowman 2002). Also, the integration of dependent tasks is less complicated than that of interdependent tasks. Therefore, several studies offered methods to mitigate complexity via the separation of interdependent tasks. For example, a well-known approach referred to as Design Structure Matrix (DSM), which was originally proposed for relationship identification, is frequently being adapted to manage interdependent tasks (Arundachawat *et al.* 2009). As part of the existing sequential design processes for P&PS (see Figure 5.1), most of the PSD tasks (i.e. system concept, system configuration, and detailed system development) require information from completed PD tasks (e.g. conceptual product design, product assembly scheme, and complete product documentation). Current integrated design predominately focuses on

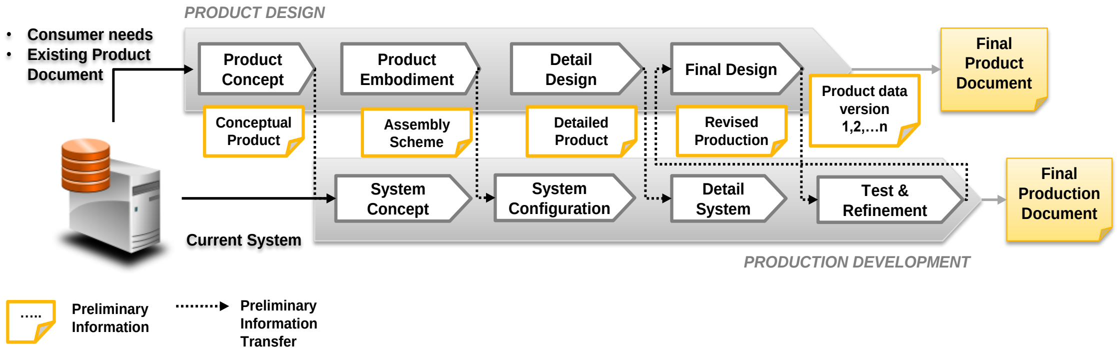


*Figure 5.1 - The interrelation of design processes of products and production systems*

timely development instead of identifying, prioritising and managing design tasks based on their significance to mitigate unexpected concerns and redesign. Moreover, these design tasks are principally formed by advancing the execution of product development (unidirectional information transfer) (Bruch and Johanssonl 2011, Stoffels and Vielhaber 2016). As a result, the critical decisions requiring collaborative considerations from various areas of expertise are often overlooked, limiting the significant potential that could be offered through a concurrent approach to co-design of P&PS.

To advance the integration of P&PS design, the critical decisions which address failures, redesign issues or ecological concerns should be carefully deliberated with sufficient knowledge and address each of these challenges; for example, Failure Modes and Effects Analysis and Life Cycle Assessment (Haapala *et al.* 2013). However, they are often used in isolation and not with visibility across both PD and PSD. Therefore, the critical decisions should be specified and evolved in such a way as to foster an interdependent relationship between design tasks based on a bidirectional flow of information and knowledge. This enables a broader range of potential benefits, including consideration of resource efficiency to be investigated across various design tasks, and more importantly from the outset of the integrated P&PS design process.#

### *5.2.2 Interaction between Design Processes*

To generate integrated tasks, the interaction between two design teams should be structurally managed. The different levels of human interaction can be described based on three different processes as follows (Lu *et al.* 2007).

#### *5.2.2.1 Coordination*

This involves *unidirectional* managing of tasks done by different teams or different hierarchies (such as management and staff) with different objectives.

#### *5.2.2.2 Cooperation*

Here we see *bidirectional* management of tasks performed by individuals or teams who share resources, procedures, and benefits.

#### *5.2.2.3 Collaboration*

This is used when the task is unachievable by an individual because of knowledge complexity and resource limitations. Lu et al. (2007) define collaboration as *"teams of individuals to work on tasks that not only have shared resources (coordination) and shared outcomes (cooperation) but most essentially, share a common goal"*(Lu *et al.* 2007).

In the majority of applications, the more advanced level of interaction (i.e. collaboration) is most likely only achievable if the preliminary interaction levels (i.e. coordination and cooperation) have already been established. The methods and tools in the existing design interactions, such as Quality Function Deployment and CAD-CAM tools (Lu *et al.* 2007), often appear to be limited in scope and only promote "unidirectional coordination" via task overlapping and information sharing (Magrab *et al.* 2009). Due to complexities in design tasks, the interactions for closely integrated design should be formed at cooperation or collaboration level using the effective implementation of communication and collaboration management. This highlights a clear need to explore the detailed nature of the required interactions within P&PS co-design to achieve targeted ecological benefits.

## 5.3 REVIEW OF RELEVANT RESEARCH

In Chapter 3, the existing concepts of integrated design have been summarised. The scope of many current studies of the integrated concept has generally been quite narrow, based on the improvement of a single characteristic of integrated design, such as information exchange or collaboration improvement. Moreover, most of these mainly aimed to meet economic targets, such as the reduction of costs and development time as opposed to achieving wider potential benefits, such as resource efficiency and improved overall sustainability of products (Short *et al.* 2012).

In order to clearly define the research gaps addressed by this research, this section investigates the research publications which are most relevant to the scope of research reported in this thesis based on:

i. a concentration on which ID characteristics (theme I - ID process, theme II - specific improvement, theme III - supporting information exchange and theme IV - strengthening collaboration),
ii. a consideration of interrelation and interaction between P&PS design
iii. responding to the environmental improvements

A summary of current methods for integrated design of P&PS is provided in Table 5.1 and discuss in the remaining sections of this chapter.

*Table 5.1 – Existing methods to implement the integrated design of product and production system*

| **Approach** | **Improvement/Utilisation of ID characteristics** | **Support the interrelation and interaction between P&PS design** | **Responding to the environmental improvement** |
|---|---|---|---|
| **The co-evolution model of products, processes and production systems.** (Tolio *et al.* 2010) | This work focused on a theme I in which this support the selection of the existing ID process approaches instead of supporting the integration of products, processes and production. | This more considered on the requirement of P&PS information instead of the interrelation and interaction between P&PS design task | No environmental consideration. |
| **Method for integrated product development oriented to sustainability** (Fernandes *et al.* 2017) | Theme III was utilised to embed sustainable production system knowledge into the product design process | There is no consideration of P&PS integration in contexts of interrelation and interaction in this work | Environmental consideration |
| **Integration framework for preliminary design and preliminary process planning (Pullan et al., 2010)** | This framework proposed new ID processes (a theme I) and a new information sharing tool (theme III) to support this new ID process. | This support P&PS design to interact at cooperation level by bi-directional information sharing between separate processes | No environmental consideration<br>(More focuses on the traditional benefits such as cost and time reduction) |

| Approach | Improvement/Utilisation of ID characteristics | Support the interrelation and interaction between P&PS design | Responding to the environmental improvement |
|---|---|---|---|
| **Decision-making system for designing products and production systems for remanufacturing activities** (Ismail *et al.* 2017) | This paper supports the specific improvement (theme II) of remanufacturing consideration in P&PS design by proposing a two-dimensional framework and tool selecting a suitable remanufacturing design approach | There is no consideration of P&PS integration in contexts of interrelation and interaction in this work | Environmental consideration<br>(More focuses on Remanufacturing) |
| **Integrated model for co-development of products and production systems** (Gedell *et al.* 2011) | This research has added the new knowledge to ID theme III by proposing the new integrated information model which illustrate the interface and interaction of P&PS | The integration was considered regarding interaction and interface between function and component of P&PS (no consideration of process and task integration) | No environmental consideration |
| **A recursive operations strategy model for managing sustainable chemical products development and production** (Choy *et al.* 2016) | The information system tool (ID theme III) was developed to support chemical product-process design and operation | There is no consideration of P&PS interrelation and interaction in this work | Environmental consideration |
| **Sustainable product development methodology** (Lacasa *et al.* 2016) | This research applied ID theme II and III to support P&PS redesign by proposing a new specific methodology and using information sharing between P&PS designs | This research did not focus on P&PS interrelation and interaction | Sustainable consideration |
| **Decision support for energy-efficient production in product and production development** (Stoffels and Vielhaber 2016) | This research has proposed a new ID process (a theme I) namely Integrated development process of P&PS | This support P&PS design to interact at cooperation level by bi-directional information sharing between separate processes | Energy efficiency consideration |

To cope with the evolution and rapid changes of systems, Tolio *et al*. (2010) proposed a co-evolution model which aims to support companies in selecting a suitable approach for configuring the product, process, and production system through the evaluations of the level of integration and usefulness of the available approaches. The model determines the integration level of an approach through the type of input information. If an approach required information related to the product, process and production system, such an approach could be considered as embodying a high level of integration. In addition to this, this model also determined when the implementation of the approach should be reviewed through the level of evolution. This can be determined by the requirement to change the input information. However, it seems that this very new concept and the proposed methods are relatively complex; therefore, there is a need for detail explanation supporting industrial implementation.

Fernandes *et al*. (2017) introduced a simple method for integrated product development oriented to sustainability, which is comprised of a three-step guideline supporting the consideration of environmental sustainability during the design process. These steps included a) categorising product and environmental impact by lifecycle phase, b) suggesting DfE strategies based on categorised product and c) give recommendation guidelines and tool support DfE suggestions related to product and production system design. Although this method attempted to utilise the ID concept to consider P&PS aspects, the production system consideration was solely considered as information support for improvement of product design rather than the holistic design of P&PS.

An integration framework for preliminary design and preliminary process planning has been introduced by Pullan *et al*. (2010) to induce manufacturing to design product and production system in parallel at an early design concept phase (see Figure 5.2). This framework provided steps for designing concept, product and production system while supporting bi-directional information sharing and two-way communication between preliminary P&PS design with an integrated manufacturing object model based on the Unified Modelling Language.

Ismail *et al.* (2017) proposed a decision-making system for supporting designing products and production systems for remanufacturing activities. Based on a large number of the available remanufacturing method and tools, this work proposed methods to classify and select suitable design approaches and tools to support P&PS design decisions. This work mainly promotes the inclusion of the production system with product consideration and does not deliver any support or suggestions for the parallel design of product and production system.

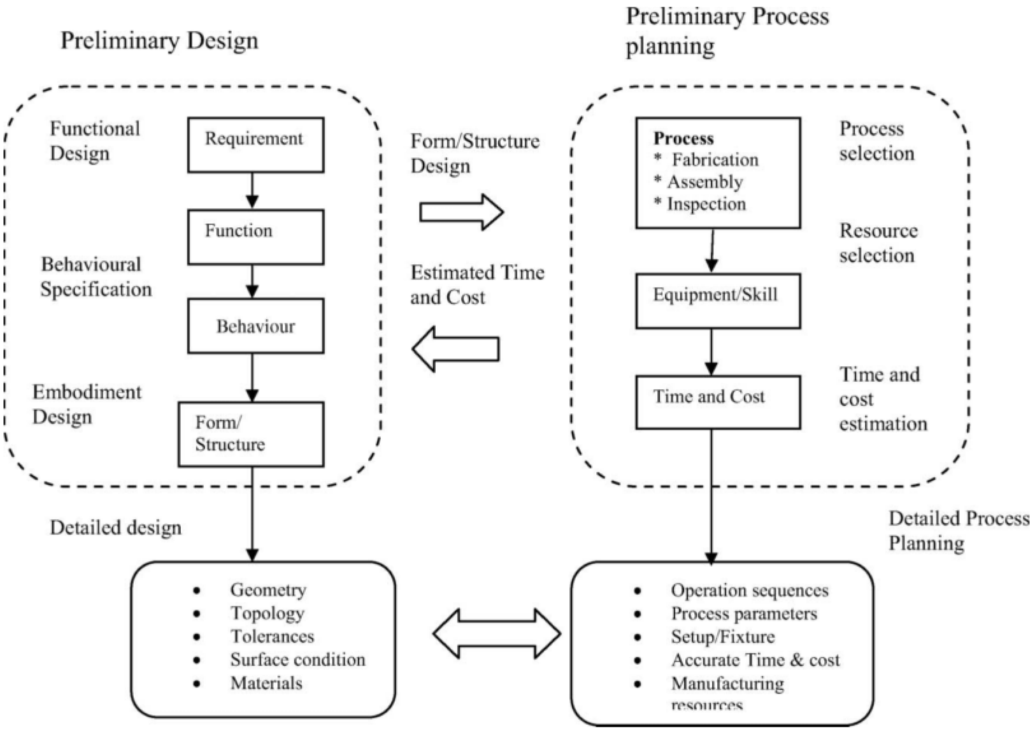


*Figure 5.2 - Integration framework for preliminary design and preliminary process planning (Pullan et al. 2010)*

In the context of information exchange, Gedell *et al*. (2011) proposed a configurable component framework for integrating information from complex products and production between component, part, and system. This aims to illustrate the interface and interaction between product and production system through the Unified Modelling Language. This can be used to collect and display the co-evolution of P&PS to support integrated design activity. This work is a useful tool to support collaborative and simultaneous P&PS design. Nevertheless, the co-equal illustration of P&PS design can cause difficulties in identifying P&PS elements; hence, the presentation of the model should be improved, keeping the uniqueness of each PD and PSD.

Choy *et al.* (2016) developed a recursive operation model to support management of sustainable chemical manufacturing by suggesting how to design an ecological policy and strategy for chemical product development and production planning. This model comprises three main steps for planning business strategy, operation strategy, and design policy. This work also proposed a Case-based Ingredient Formulation Module and a Fuzzy-based Parameter Determination Module to support historical P&PS data during design policy. It aims to support the specific design of chemical products and production systems by reducing resource use during the design and development phase.

To support ecological implementation at the operation level, Lacasa *et al*. (2016) offered a three-stage framework called sustainable product development methodology. This has been developed to improve sustainable manufacturing systems by incorporating resource consumption of production processes and life cycle assessment into product redesign. However, the potential benefits of ecological considerations through this proposed framework are limited, since the integrated consideration of product and production system is only applied at a late stage during the manufacturing phase.

For another application at the operational level, the integrated development process of products and production systems was established to suggest how manufacturing can implement ID concepts (Stoffels and Vielhaber 2016). This work manages integrated design during concept design and component design, using iterative information sharing between the two design processes. In addition, during integration design, an energy efficient manufacturing method was proposed to support the appropriate design with low energy consumption. This work also supports the requirement of integrated design to mitigate the present challenge of environmental crisis, particularly the energy issue, which was highlighted in the previous chapter.

In conclusion, it can be seen that far too little attention has been paid to the integrated design of product and production system. The literature under review has highlighted the emergence of research attention in considering a product together with its production system. Nevertheless, only a few publications, by Gedell *et al*. (2011), Pullan *et al*. (2010) and Stoffels and Vielhaber (2016), directly explored and developed support for integrating the design of P&PS. Therefore, there still a gap in fulfilling the need to truly aid manufacturers in integrating product and production system, especially in the context of design process integration in order to maximise the resource efficiency (including materials, energy and water) of manufacturing.

## 5.4 SUMMARY OF MAIN FINDING FROM LITERATURE REVIEW CHAPTERS

The integrated design of product and production system has generally been utilised for a separated but concurrent development approach rather than the combined consideration of P&PS design in one single process. Currently, integrated concepts are frequently applied to shorten development time through the early stages of the design process. For example, according to DfM, manufacturability is generally considered during the late detailed design stage. This practice still cannot truly prevent possible failure and redesign issues based on the lack of knowledge and inability to effectively evaluate the impact of product design decisions on production systems requirements (Lumsakul *et al.* 2018).

More importantly, this ‘fix it later’ approach also appears to be present in sustainable design and manufacturing applications, in which the potential benefits are limited by the late consideration of sustainability issues within the design process, and/or inability to fully assess the direct and indirect impacts of proposed product design improvements within production facilities. Manufacturers are often unwilling to replace the existing production processes with ones that produce lower ecological footprints and require less resource consumption if the significant additional investment is required. Hence, designers should equally consider the design of the product and production system equally at an early stage of the design process. In order to do so, there is a need to clearly understand the relationship between product and production system design, to be able to identify and assess design decisions which impact on the improvement of resource consumption as well as select the most environmental-friendly options.

To achieve this, the next level of closer integration should be realised through a single combined design method capable of delivering the ability to assess the impact of recommendations and changes throughout P&PS design processes. For example, the impact of materials substitution for improved recyclability or the impact of adopting new production system design which is more energy-efficient technologies and are lower impact non-chemical processes on product design can be assessed directly.

Therefore, this research proposes an evolution towards a combined design process of product and production system, refer to as Co-design of P&PS (See **Error! Reference source not found.**). Such novel design concept provides the ability to gain insight into the impact of various possible design improvements and enable what-if scenario planning to maximise the potential for resource efficiency. Moreover, this concept of co-design of P&PS is expected to provide other benefits, including reduction of cost and development time, improved quality and manufacturability of products, and the opportunity for reacting to market changes as well as the ability for mass customisation and personalisation of product designs, as shown in Figure 5.3.

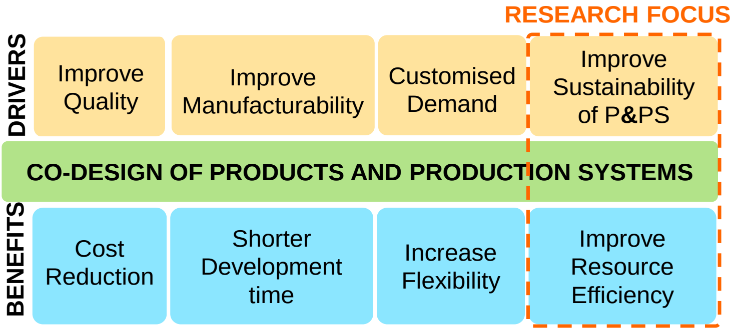


*Figure 5.3 – Drivers and benefits of co-design of P&PS*

# CHAPTER 6 RESEARCH METHODOLOGY

## 6.1 INTRODUCTION

This chapter outlines the methodology adopted in performing the research reported in this thesis. The first two sections of this chapter explore an overview of existing research methodologies, including research definition, research types, and research methods used in diverse fields of study beyond the design discipline. Then, the third section details the methodology applied in this research.

## 6.2 DEFINITION, TYPES AND METHODS OF RESEARCH

The Cambridge Dictionary has defined 'research' as *"a detailed study of a subject, especially in order to discover new information or reach a new understanding"* (Cambridge University Press 2016). With reference to various definitions of research, the term's meaning has been comprehensively expressed as *"the systematic method consisting of clarifying the problem, formulating a hypothesis, collecting the facts or data, analysing the facts and reaching certain conclusions either in the form of solution(s) towards the concerned problem or in certain generalisations for some theoretical formulation"* (Kothari 2004)

Kumar (2011) has suggested that research can be classified based on different perspectives of application, objective and information type, as depicted in Figure 6.1. From the application perspective, the main two types of research are pure research and applied research. Pure research (or basic/fundamental research) is principally concerned with generalisation, theoretical formulation, and natural phenomena, e.g. the discovery of new scientific knowledge or new pure mathematics. On the other hand, applied research, such as most research in the social sciences, aims to find solutions for situations related to social, economic or political trends (Kothari 2004). For the objective perspective, research endeavours can be classed as descriptive, correlational, explanatory, and exploratory. Descriptive research tries to explain a particular situation, problem, phenomenon or service regarding a group of people or a community systematically (e.g. attitudes of students towards the quality of teaching). The purpose of correlational research is to verify the existence of a relationship between related aspects of a condition.

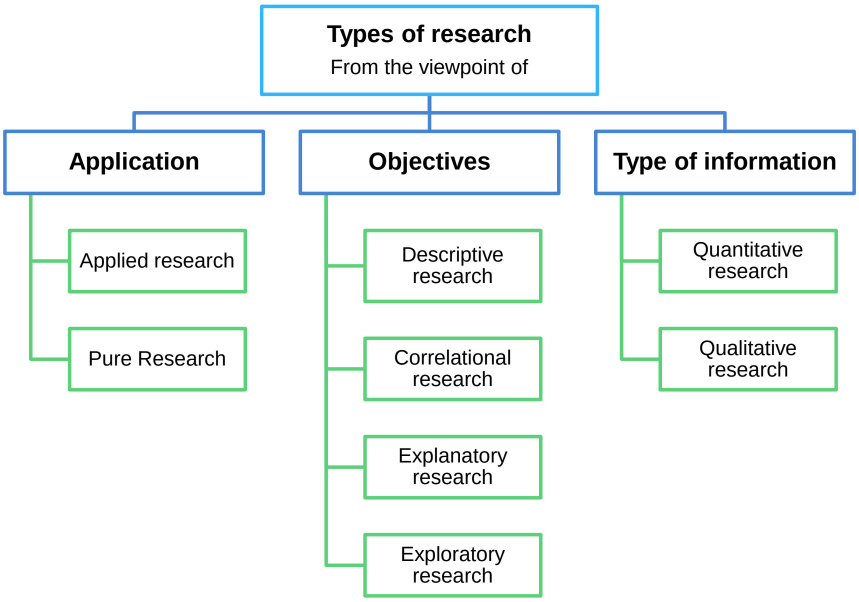


*Figure 6.1 - Types of research (Kumar 2011)*

The explanatory research aims to investigate further why and how an existing relationship has formed. The last type of research regarding objectives is exploratory research, which is commonly known as feasibility or pilot study for determining the possibility of a full-scale research project. This type of research is to confirm worthiness in conducting full-scale research in an unexplored area. From the viewpoint of information measurement, research can be classified into qualitative and quantitative research.

The qualitative research attempts to define a situation, phenomenon, problem or event via variable measurement using nominal or ordinal scales, whereas quantitative research aims to quantify the variation in a situation, phenomenon, or problem (Kumar 2011).

In addition to these research types, Kothari (2004) has systematically categorised research based on research methods into three types: library research, laboratory research and field research. Library research can be processed by an analysis of historical records and an analysis of documents, whereas laboratory research is generally conducted by small group study of random behaviour, play or role analysis. For field research, applicable research methods include non-participant direct observation, participant observation, mass observation, mail questionnaire, opinion survey, personal interview, focused interview, group interview, telephone survey, case study and life history.  Overall, research methods are typically used for three primary purposes:

collecting data, establishing relationships between the data and the unknown, and evaluating the accuracy of results.

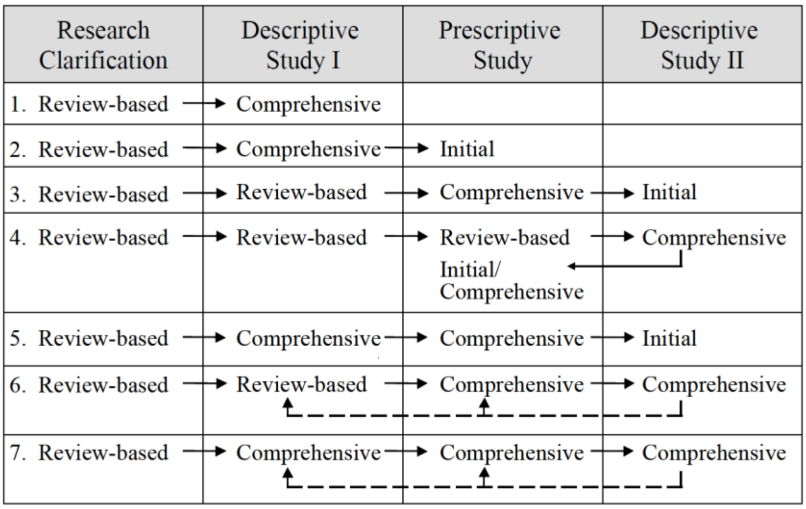
## 6.3 RESEARCH METHODOLOGY

Nayak and Singh (2015) have defined a term ‘Research methodology’ as *“a research strategy that translates ontological and epistemological principles into guidelines that show how research is to be conducted and principles, procedures, and practices that govern research…The selection of research methodology depends on the paradigm that guides the research activity, more specifically, beliefs about the nature of reality and humanity (ontology), the theory of knowledge that informs the research (epistemology), and how that knowledge may be gained (methodology).”* The present research concern product and production system design, the existing methodology for design research was reviewed in the next section.

### *6.3.1 Research Methodology in Design*

According to Blessing & Chakrabarti (2009), design research aims *“to make the design more effective and efficient, in order to enable design practice to develop more successful products”.* To satisfy this, a Design Research Methodology which consists of four steps, namely research clarification, descriptive study I, prescriptive study, and descriptive study II has been proposed (Blessing and Chakrabarti 2009). With research clarification, researchers intend to formulate a realistic and valuable research goal (to link influential factors, design problems and an existing situation) by searching in the literature. In the descriptive study I step, researchers aim to refine the factors influencing the research goal (e.g. product success) by elaborating a comprehensive description using further literature review or empirical data analysis (e.g. by observing and interviewing designers at work). Next, researchers develop possible solutions or scenarios based on a clear understanding of the existing and desired situation at the prescriptive study step. Finally, the descriptive study II step is designed to investigate the impact of the developed solutions/support/scenarios and their ability to realise the desired situation to improve and refine the development. In reference to these steps, seven possible pathways for design research are recommended (see Table 6.1). The review-based study is based only on literature review, and a comprehensive study is a combination of literature review and an empirical study

*Table 6.1 – Types of design research projects and their focus according to (Blessing and Chakrabarti 2009)*



| Research Clarification | Descriptive Study I | Prescriptive Study | Descriptive Study II |
|---|---|---|---|
| 1. Review-based → | Comprehensive | | |
| 2. Review-based → | Comprehensive → | Initial | |
| 3. Review-based → | Review-based → | Comprehensive → | Initial |
| 4. Review-based → | Review-based → | Review-based →<br>Initial/ Comprehensive ← | Comprehensive |
| 5. Review-based → | Comprehensive → | Comprehensive → | Initial |
| 6. Review-based → | Review-based → | Comprehensive → | Comprehensive |
| 7. Review-based → | Comprehensive → | Comprehensive → | Comprehensive |

or development by the researcher. Furthermore, an initial study may be undertaken, or subsequent research will complete it through result presentation, discussion and preparation for further use.

## 6.4 RESEARCH METHODOLOGY ADOPTED IN THIS THESIS

The research methodology adopted in this project is in line with the Design Research Methodology approach type 5. The methodology can be divided into four distinct phases, which are research clarification, framework and model development, testing and validation, and research conclusions (see Figure 6.2). The steps within and details of each phase are described as follows.

The first phase intended to clarify the research hypothesis, which requires sufficient knowledge concerning the research topic. Therefore, this phase involved a systematic investigation of existing knowledge, including the author’s prior knowledge gained through work experience in the subject area, the related literature (integrated design drivers, design processes, and sustainability in product and production system), and industry practices. As the result of knowledge exploration through the current situation, challenges and opportunities of integrated design, sustainable design, and resource efficiency, a clear need for the combined design of product and production system for resource efficiency was highlighted. Moreover, interrelations and interactions between design processes were clarified to examine further how the design of product and production system are currently integrated. This would provide support to current manufacturers and designers to improve the resource efficiency of the product and production

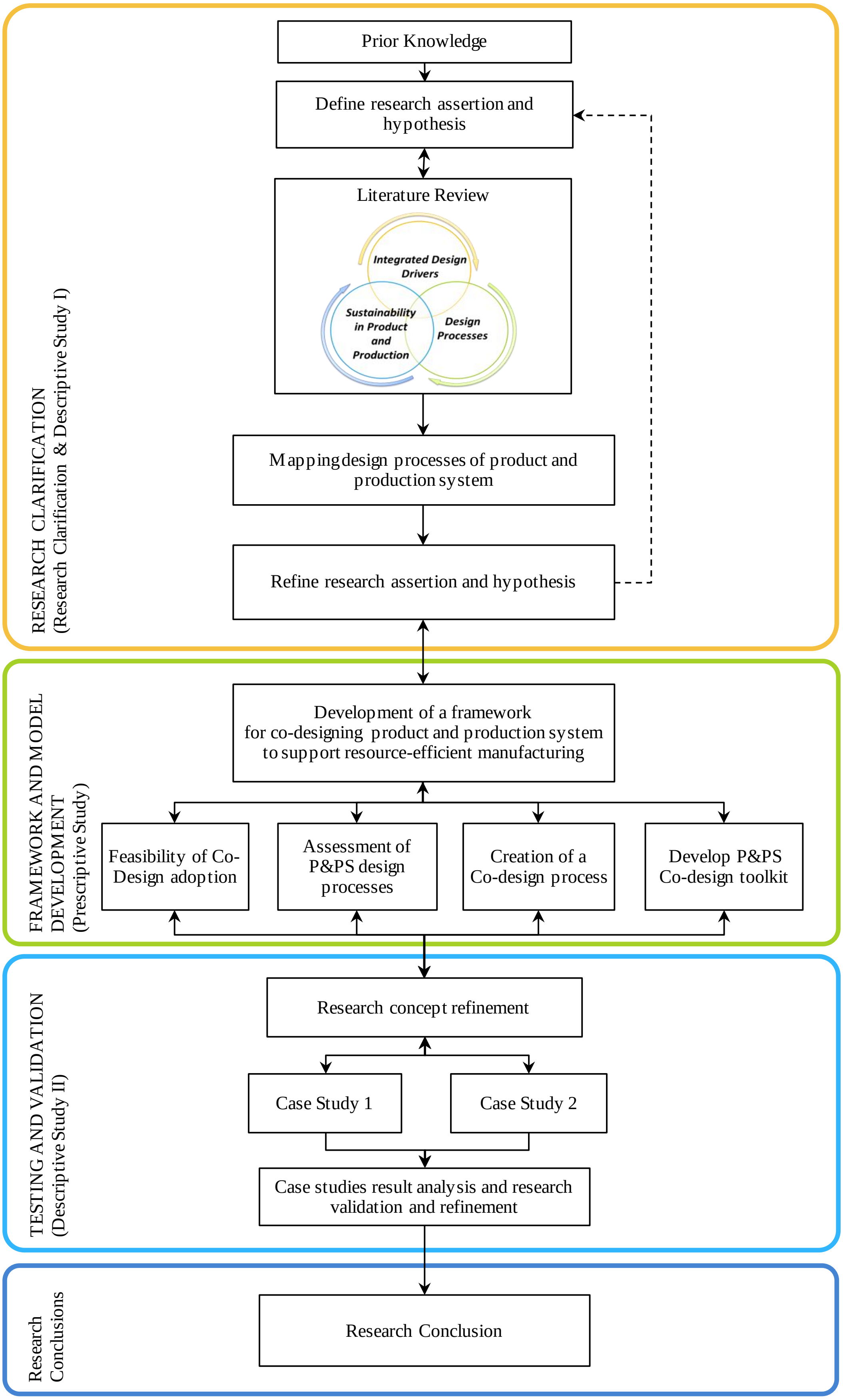


*Figure 6.2 – Research Methodology Diagram*

system during the development phase. To this end, research objectives and scope were then established to achieve the aim with systematic working steps.

Based on this examination and the findings during the previous phase, a framework for co-designing (integrating) product and production system for resource-efficient manufacturing was then developed in the second phase. This framework was designed to assist manufacturers in identifying the requirements of integrated design, examining which design decisions should be jointly considered to improve the resource efficiency of product and production system, suggesting how these collaborative design decisions are generated, and implementing this framework with an applicable toolkit. Therefore, this phase also covered the development of methods for studying the feasibility of co-design adoption, assessing design processes, creating a co-design process, and developing a supporting toolkit.

The third phase involved testing, validating and refining the proposed framework through two case studies which test different applications of the framework in different manufacturing industries. The first case study was applied with manufacturing companies who have simple design processes for developing simple products and production systems. Then, another case study was implemented in a company which generally designs complex products making use of complex production processes. Data was collected through a combination of email exchanges, telephone interviews, face-to-face interview and questionnaires. The result of the validation can be used for improving the framework.

The fourth phase was to report the research conclusions, including the results of the research from the previous phase, the new knowledge that this research has contributed in the research area, and further research and development for sustainable integrated design.

## 6.5 CHAPTER SUMMARY

This chapter presented an overview of research methodology, including the difference between research method and research methodology and descriptions of different research types, research methodology in design and the research methodology adopted in this work. The four main phases of the adopted methodology were explained, in which the detailed work of the first phase has been provided in Chapters 1 – 5. The details of research conducted during the last three phases are presented in Chapters 7 – 10, Chapter 11 and Chapter 12-13, respectively.

# CHAPTER 7 A FRAMEWORK FOR THE CO-DESIGN OF PRODUCT AND PRODUCTION SYSTEM TO IMPROVE RESOURCE-EFFICIENCY

## 7.1 INTRODUCTION

This chapter introduces a framework for co-designing the product and production system to support resource-efficient manufacturing. Based on the results from the literature review, this framework is proposed to reduce resource consumption of production through co-design (combined design) of product and production system. First, this chapter defines a term of Co-design adopted in the framework. Subsequently, the following section gives an overview of the co-design framework including its objectives, structure and a brief explanation of its four main phases.

## 7.2 THE DEFINITION OF CO-DESIGN IN THIS RESEARCH

In the literature, the term ‘co-design’ tends to be used to refer to an activity or process where problems, ideas, and decisions are deliberated between the designer and non-designers (i.e. the recipients of the design, such as customers, consumers, and users) to clarify better the requirements for designing the product or service (Taffe 2015). For instance, Steen *et al*. (2011) defined co-design as activities where *“diverse experts come together, such as researchers, designers, developers, (potential) customers, and users who are also experts (of their experiences) to cooperate creatively”* during design processes.

Bradwell and Marr (2008) provide a slightly different definition of co-design based on participation, development, ownership and the outcome as *“the effort to combine the views, input and skill of people with many different perspectives to address a specific problem.”*

In this research, it should be noted that the term “co-design” refers to the predicted future of the conventional Integrated Design (ID) concept and is defined as **‘a single combined process to simultaneously design the product and production system required to manufacture them’**.

## 7.3 A FRAMEWORK FOR THE CO-DESIGN OF PRODUCT AND PRODUCTION SYSTEM TO IMPROVE RESOURCE-EFFICIENCY

The majority of current sustainability initiatives in the manufacturing sector focuses on the improvement of production processes, technologies and systems. Consequently, these improvements are considered to result in only incremental ecological benefits. These methods, however, cannot satisfy the contemporary and urgent requirements posed by environmental considerations. To achieve the desired radicle improvements, a manufacturing company should consider the design of its product and its production systems concurrently the author asserts that a manufacturing company should consider the design of its product and its production systems concurrently. Therefore, this research has defined a framework which is a stepwise approach to combining the consideration for the design of P&PS in a single process. The P&PS co-design aims to develop a more collaborative design method for concentrating on the improvement of resource efficiency as shown in Figure 7.1. In addition to ecological benefits, this new co-design process is expected to provide other benefits, including reduction of cost and development time, improved quality and manufacturability of products, and the opportunity for mass customisation and personalisation of product designs.

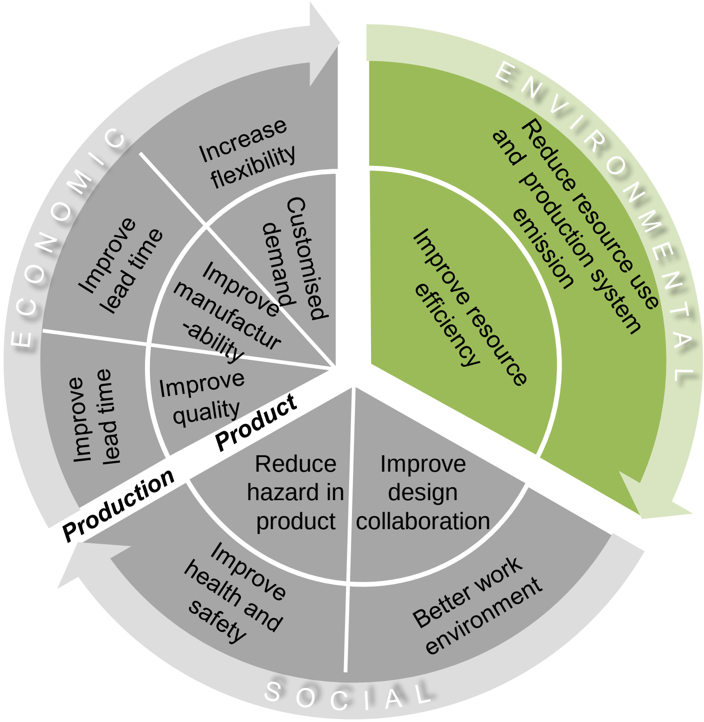


*Figure 7.1 - The requirements of environmental considerations in an integrated design concept*

To implement a single co-design process, this research proposes a novel framework in which crucial design decisions related to resource-efficiency improvements will be identified and addressed through simultaneous collaboration between designers. The improved collaboration provides the ability to gain insight into the impact of various possible design improvements and enables what-if scenario planning to maximise the potential for resource efficiency. For instance, through the exchange of knowledge, P&PS designers can collaboratively choose from broader options, such as materials substitution for improved recyclability, new more energy-efficient technologies, or low impact non-chemical processes within the production system. Also, the flexibility offered through co-design not only facilitates the requirement for frequent changes imposed by market conditions but also removes obstacles in enhancing resource efficiency during the manufacturing phase.

Moreover, guidance and methods are provided to identify the benefits of co-design adoption, specify the requirements for collaboration between design processes, and to organise more streamlined design process for manufacturers. This framework, labelled P&PS Co-design, consists of four main phases, namely Co-initiate, Co-specify, Co-create and Co-implement, as shown in Figure 7.2 and are briefly described in the remaining sections of this chapter.

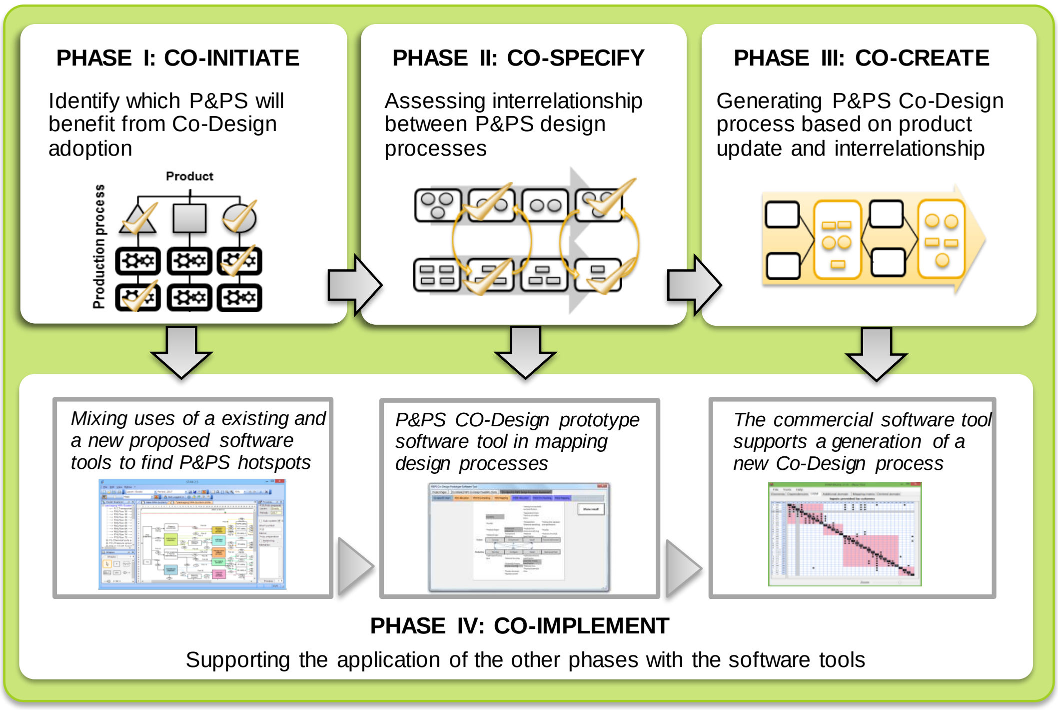


*Figure 7.2 - A framework for co-designing products and production systems to support resource-efficient manufacturing*

### *7.3.1 Phase 1: Co-initiate*

The first phase provides an approach to determine the potential benefits to be gained from P&PS co-design adoption. The manufacturing company is therefore able to indicate which design processes of P&PS should be combined to minimise resource use. The Co-initiate phase can be performed through two main activities, as depicted in Figure 7.3.

The first step begins with the collection of the relevant P&PS design data, e.g. the person in charge of each activity, product list, product structure, and so on, to define the goal and scope of co-design consideration clearly. Then, a P&PS co-design feasibility study is undertaken based on consideration of three main factors; the frequency of design updates, the potential impact of design changes between P&PS, and the resource efficiency of the production system. The principal output of this phase is an overall assessment of P&PS co-design suitability for the product and/or product family under consideration.

### *7.3.2 Phase 2: Co-specify*

Based on the feasibility assessment, the main objective of the Co-specify phase is to identify which P&PS design decisions have a direct and indirect impact on resource efficiency. This phase consists of three main steps as shown in **Error! Reference source not found.**. The first step analyses the impact of a design decision on resource consumption. Then, the second highlights the interrelation between these P&PS design decisions and the third aims to suggest the most suitable strategy for applying a single co-design process within a company.

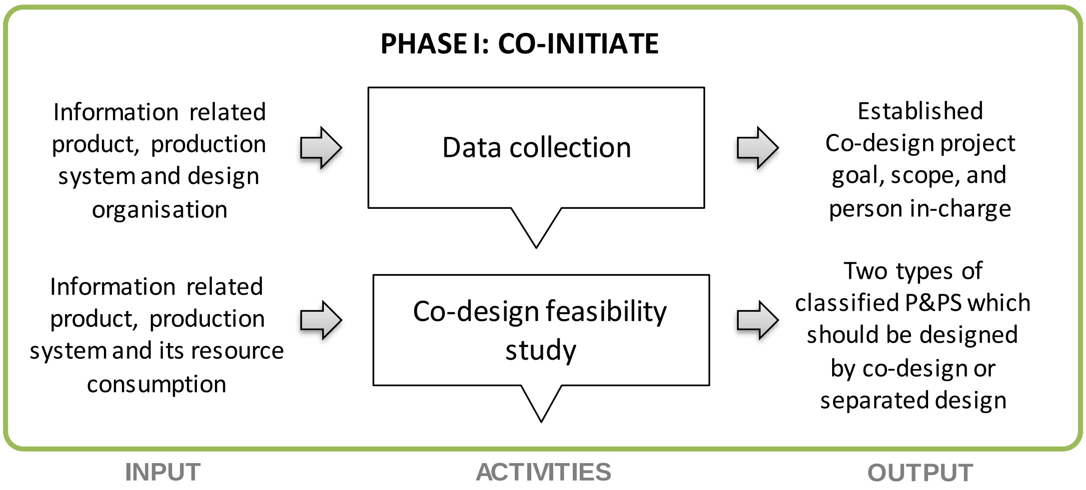


*Figure 7.3 - Fundamental activities during the Co-initiate phase*

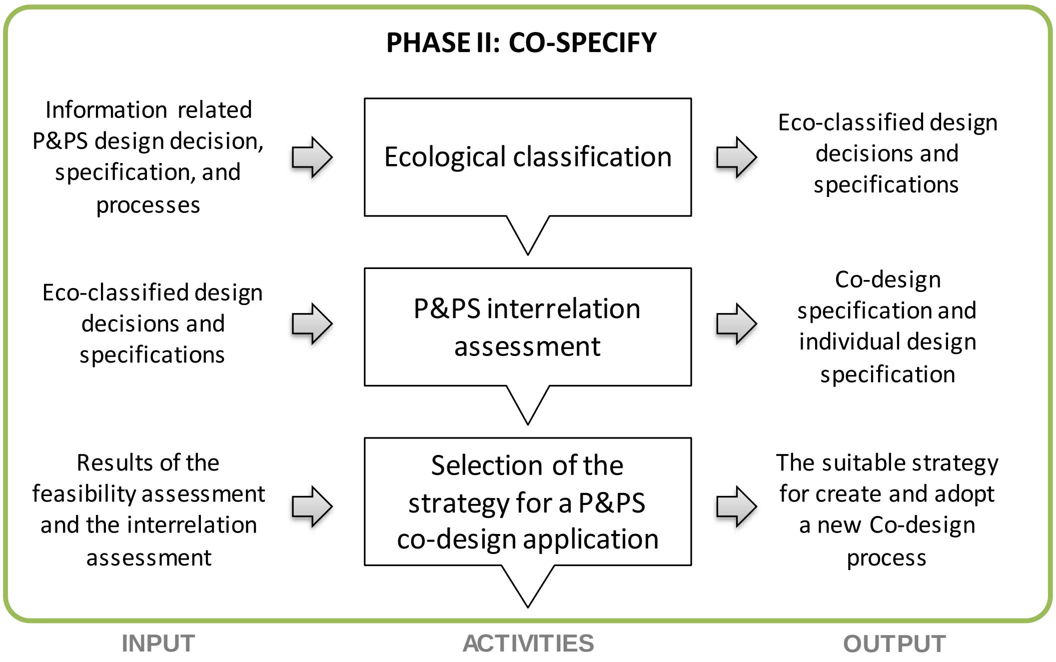


*Figure 7.4 - Fundamental activities during the Co-specify phase*

### *7.3.3 Phase 3: Co-create*

In the third phase, the strategies are considered for implementation of P&PS co-design process. These strategies are based on 'Awareness' of knowledge interchange, 'Association' between design team through better collaboration, and 'Adaptation' to a single design process, as depicted in Figure 7.5. The selection of one of these strategies for implementation of P&PS co-design is

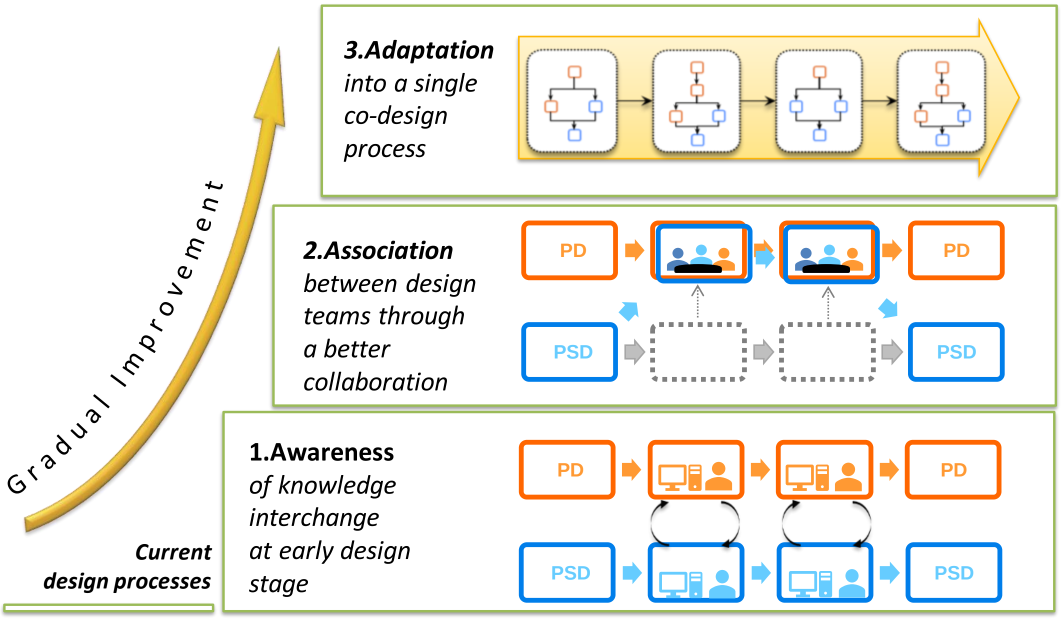


*Figure 7.5 - The proposed 3A strategy used during the Co-create phase*

very much dependent on the specific product attributes and manufacturing company characteristics (e.g. size, sector, market, etc.). These three strategies could also offer a gradual path from existing design to P&PS co-design process for a manufacturing company. With Awareness strategy, the product and production system are still designed using two different processes but in a much more coordinated approach. In association strategy, a subset of design processes is combined, whereas in adaptation strategy the entire design process is replaced by a single combined P&PS co-design process.

### *7.3.4 Phase 4: Co-implement*

The Co-implement phase supports the implementation of the three preceding phases using a specially developed P&PS co-design prototype software tool, along with other available commercial software tools as shown in Figure 7.6. The use of these software tools is not only to provide guidance in the form of a framework application but also for identifying the data required for the operation of a single P&PS co-design process. The prototype software developed by this research aims to support the significant data processing involved in Co-initiate, Co-specify and phases. The choices of existing commercial software will depend on the specific strategy adopted as part of Co-create.

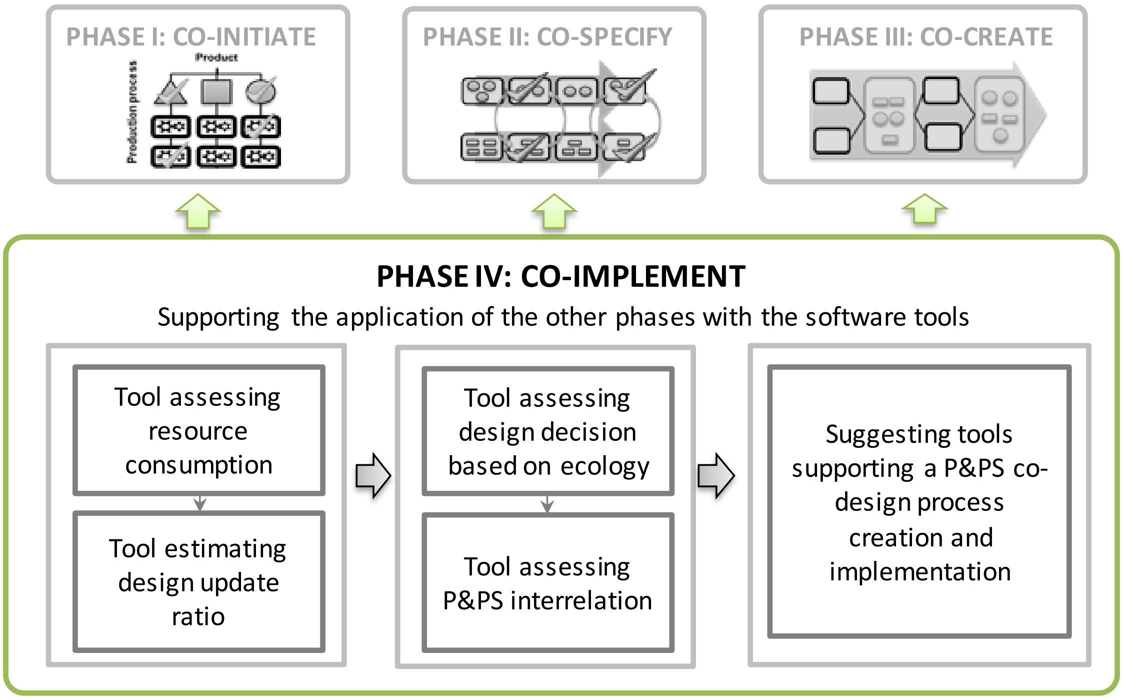


*Figure 7.6 - Fundamental activities in the Co-Implement phase*

## 7.4 CHAPTER SUMMARY

This chapter has presented the step-wise approach in the P&PS co-design framework which is implemented to enable a seamless and rapid decision making regarding the suitability of co-design application. In phase 1 (Co-initiate), the design frequency change and resource intensiveness in the application are considered to make the first decision, i.e. is co-design suitable for this application or not. The second phase (Co-specify) identifies where the collaboration in decision making is required and depending on a number of potential collaboration requirements; it decides which of three strategies (defined in phase 3) should be adopted as a starting point for implementation of co-design in a company. Phase 3 (Co-create) then utilises the selected strategy to identify areas of collaboration and how best to achieve this. Finally, in phase 4 (Co-implement), the specific requirement in the application is used to identify any appropriate existing tools that could be used by a company to aid the creation and implementation of co-design. The following chapter will further discuss the first two phases in full detail to perform a co-design feasibility study and a design process assessment.

# CHAPTER 8 CO-INITIATE AND CO-SPECIFY IN THE P&PS CO-DESIGN FRAMEWORK

## 8.1 INTRODUCTION

An overview of the P&PS Co-design framework was introduced in the previous chapter. In this chapter, phase one and two of the framework, namely the Co-initiate and Co-specify will be explained in more detail. The Co-initiate phase aims to perform a co-design feasibility assessment based on the key characteristics of a product and its production systems, and the Co-specify phase will guide designers to define the critical decisions related to the co-design process.

## 8.2 PHASE 1: CO-INITIATE PHASE

This research proposed the novel P&PS Co-design framework to support manufacturing companies in coping with the present design challenge by replacing current independent P&PS design processes with a new co-design process. Commonly, any changes to a method or tool in manufacturing usually require an investment of time and/or money. The first phase of the P&PS Co-design framework therefore aims to investigate the feasibility of co-design adoption and to confirm the potential benefits, before recommending any changes to the current design processes.

In the past, manufacturing companies generally introduced new design very infrequently. This meant a rigid production system could be designed and operated for a long period of time for a mass production approach. In such cases, the traditional design process of P&PS was able to satisfy the simple market requirement of infrequent product updates, with very limited changes to production system and high availability of natural resources. However more recently, market requirements have significantly changed and became more complicated, with various requirements such as higher product quality, lower cost, product updates for market stimulation, and sustainability considerations (Ramani *et al.* 2010, Sheldrick and Rahimifard 2013). The novel P&PS co-design process is proposed for a better response to these challenges (see Table 8.1).

*Table 8.1 - The difference between the traditional design process and a co-design process based on P&PS characteristics.*

| P&PS CHARACTERISTICS | TRADITIONAL/INDEPENDENT DESIGN PROCESS | CO-DESIGN PROCESS |
|---|---|---|
| **A frequency of design update** | Low product design update | Frequent product update |
| **Level of the interrelation between P&PS design update** | Low level of P&PS interrelation | High level of P&PS interrelation |
| **Requirements for improving resource efficiency via design** | Low requirement due to low resource consumption | High requirement due to resource intensive product |

Hence, this phase utilises the three key considerations of the required frequency of design updates, the level of interrelation between P&PS design activities, and the requirements for improving resource efficiency through design for assessing the feasibility and suitability of co-design process of a given product and product family. Also, the Co-initiate phase aims to highlight the P&PS candidates in which their design processes need to be improved. In this context, candidates are defined as **'P&PS that their design decisions necessitate changes in both design processes in order to enhance the overall resource efficiency of P&PS'**.

The Co-initiate consists of five tasks (see Figure 8.1), which are listed below and described further in the following sections:

i. Collection of relevant data for both product and production system design data
ii. Identifying the required frequency of design updates
iii. Defining the interrelation between P&PS design updates
iv. Measuring resource consumption of key processes in the production system
v. Identifying the candidates for P&PS co-design processes based on the results in task 2-4

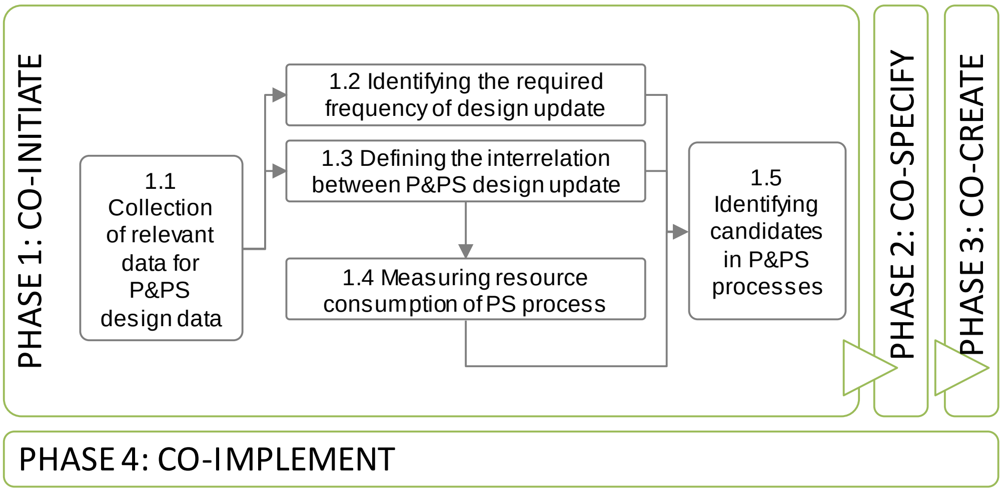


*Figure 8.1 - Overview of activities in the Co-initiate phase*

### *8.2.1 Step 1.1: P&PS design information collection*

The first task in the Co-initiate stage requires the collection of relevant information related to the structures of design processes. This includes basic information used for setting goals, objectives, scope, company name, project start date, a person in charge, other stakeholders, and finally a list of products (or product families) and production systems under consideration in the co-design project. Other information required for the feasibility study in Co-initiate phase is the frequency of P&PS design updates, the service life of P&PS, and resource consumption associated with key processes in the production systems.

Additionally, this information is used to define whether a company currently applies a simple or complex design process structure. The identification of design process structure is required because a simple and complex design will use the different framework approaches, particularly in the second phase (design processes assessment).

**A simple design process** is commonly used to design a simple product such as sporting goods and furniture. As mentioned in Chapter 3, this linear process comprises of several design stages and managed by a central design organisation (Sheldrick 2015). All design activities in this type of organisations are performed in-house and controlled by a small group of designers. Changes in design processes are flexible, simple and easy to implement since there is no additional complication in co-design based on design authority and control aspects.

On the other hand, **a complex design process** is applied to systematically design a complex product, its parts and its components. In general, during the early period of this process, design activities are managed by various design teams who are specialised in different PD techniques. Then, after the design concept is selected, the different design teams parallelly complete the design of each part and component. In this design nature, a complex design process is regularly managed by a distributed design organisation. Also, the improvement or change of this complex design could be more difficult depending on product characteristic. For example, the change in the design of complex products (i.e. chassis and jet-engine) could be highly limited due to high risk, high sensitivity and the requirement of high quality. Hence, there is more difficulty in processing the co-design framework due to the need for information collected from various stakeholders. To implement a single co-design process, an advanced technological tool is required to support information sharing and decision making throughout the design process.

Importantly, these activities should be handled by a team of co-design operators who have different backgrounds of product design, production system design and sustainability. Importantly, these operators should be the experienced staff and have a matured knowledge. In detail, at least one of co-design operators should have a mature knowledge related an assessment of resource consumption to support the implementation of Co-initiate phase; therefore, this operator should be staff from the environmental department or out-sourcing environmental consultant. Moreover, the co-design operator from design departments should 1) understand the structure of their existing design processes, 2) realise actual collaboration between design teams, and 3) be able to authorise the improvement of collaboration. Therefore, the application of framework phase two to four can be effectively performed. In sum, regarding the collected information, the co-design operator may then continue the co-design feasibility assessment as detailed in the following steps.

### *8.2.2 Step 1.2: Identifying the frequency of P&PS design updates*

This section aims to identify the chance to embed the consideration of resource efficiency during the design phase. Therefore, the often update product is more likely to have more chances of resource efficiency consideration through a production system design (the design of production is considered in the following step). In some products, frequent design update has led to an increasing demand of unnecessary products and rapidly replace their functioning products to maintain modernity. The higher updates of new product designs result not only resource consumed during P&PS manufacturing, but also increases waste from functioning products. Even so, many studies have extensively underlined the relationship between frequent product updates and resource consumption, while only a small number of studies offer applicable methods for estimating this relationship. The following equation concerning Product Design Update (PDU) rate is proposed to define the requirement of Co-Design and to estimate resource efficiency in a product design update context. The product design update rate can be calculated based on a ratio between a Frequency of Product Design ($FPD = P_{n+1} - P_n$) updates and Product Service Life ($PSL = T_e - T_s$) as illustrates.

Equation 8.1 $$PDU = 1 - \frac{P_{n+1} - P_n}{T_e - T_s}$$

$P_n$ : the start time of the development of product model n

$P_{n+1}$ : the start time of the development of product model n+1

$T_s$ : the start service time of product model n

$T_e$ : the end service time of product model n

The product design update rate can be calculated as a ratio between the frequency of product design update and product service life. An interpretation of a value of PDU can be classified into one of two categories:

If $0 \leq PDU < 1$, the evaluated design has frequent updates and might be considered an example of planned obsolescence. At this point, the adoption of the Co-design process relies on an effect between P&PS design update and resource consumption of production systems. The PDU results of the products which could be included in this range are shown in **Error! Reference source not found.**.

If $PDU < 0$, the design of product or production process might be continued using the current conventional design process, which can be satisfactory for infrequently updated product manufacturing with mass production patterns. Moreover, this design mode might further improve design durability, in that it conserves resource consumption from the replacement of the current design.

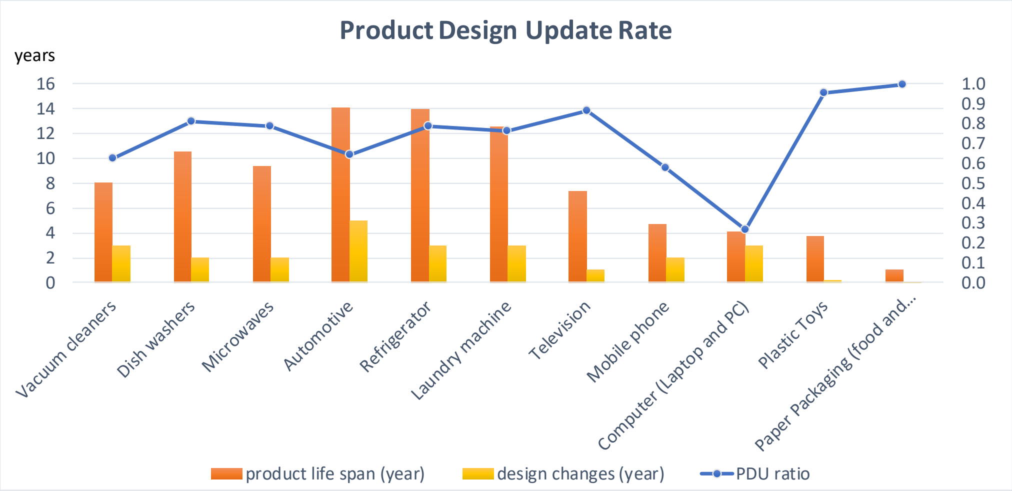


*Figure 8.2 – Example of PDU results from different products*

*Table 8.2 – Source of data for PDU determination*

| **Product Type** | **Product Lifespan (Year)** | **Design Changes (Year)** | **Data source for Lifespan** | **The data source for Design Change** |
|---|---|---|---|---|
| Vacuum cleaners | 8 | 3 | (Bakker *et al.* 2014) | Interview |
| Dishwashers | 10.5 | 2 | (Bakker *et al.* 2014) | Interview |
| Microwaves | 9.4 | 2 | (Bakker *et al.* 2014) | Interview |
| Automotive | 14.1 | 5.0 | (SMMT 2017) | Interview |
| Refrigerator | 14.0 | 3.0 | (Horie 2004) | Interview |
| Laundry machine | 12.5 | 3.0 | (Stamminger *et al.* 2018) | Interview |
| Television | 7.4 | 1.0 | (Chris 2014a) | Interview |
| Mobile phone | 4.7 | 2.0 | (Chris 2014b) | Interview |
| Computer (Laptop and PC) | 4.1 | 3.0 | (Bakker *et al.* 2014) | Interview |
| Small Toys | 3.7 | 0.2 | (Bakker *et al.* 2014) | (McDonald 2015) |
| Paper Packaging (food and consumer good) | 1.0 | 0.003-0.167 | Interview | Interview |

Moreover, this PDU equation intends to present a concordance between the frequency of a single design update and its service life, excluding the comparison of design updates between different product types regarding the variety of resource consumption pattern and utilisation.

### *8.2.3 Step 1.3: Defining the interrelation of change between P&PS design*

The interrelation of change between P&PS design is considered in order to support the consideration of resource-efficient strategies at an early stage of the design process. Regarding literature finding, resource efficient strategies can be realised through a change within production system which can be a process flow/layout change, a production process change and/or a machine tool change (see Figure 8.3). Hence, any product design updates which lead to one of these

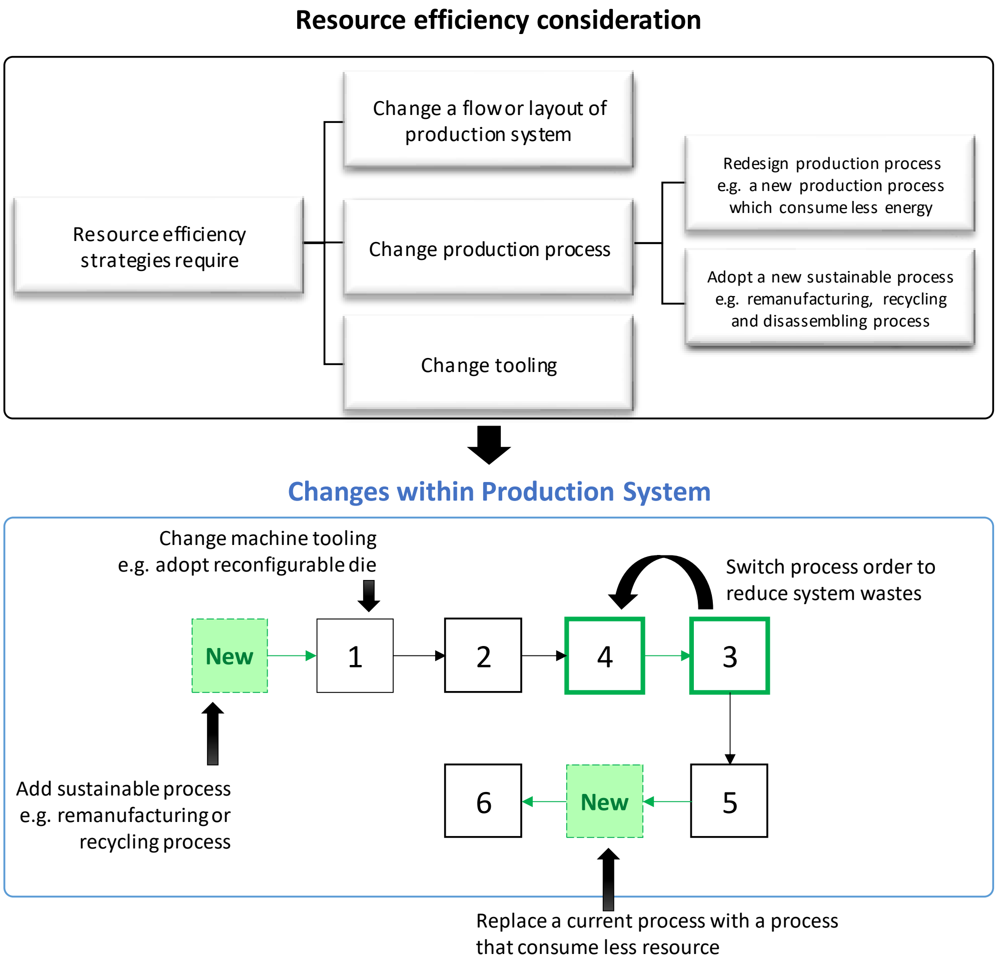


*Figure 8.3 – A consideration of change within the production system*

production system changes are the opportunities to improve the resource efficiency of the production system. This step therefore identifies the production system which changes based on product design update through the interrelation of change between P&PS design.

In detail, this interrelation of change can be measured directly by comparing the Frequency of Product Design (FPD) updates with the Frequency of Production System Design (FPSD) change which can be a change of process flow/layout, a production process or a machine tool. This can represent the responsiveness of the production process in connection with the change of product design. More specifically, the relationship required to consider co-design feasibility can be classified into two categories as follows:

If **FPD = FPSD**, it means that the design of the production system is highly depended on product design. In this case, a co-design process is considered more suitable for the co-creation of the product and its production system than the current separated design processes. This is especially valid when co-design is applied to improve the resource efficiency of the production system. This consequently provides economic benefits where one can produce more products with fewer natural resources. For instance, a change of geometry in a shampoo or detergent package generally requires a new plastic injection mould for production. In this case, the consideration of the ecological aspect during P&PS co-design could provide higher benefit than a currently separated design of P&PS with only a belated consideration of resource use.

If **FPD ≠ FPSD**, it means that any updates in product design did not necessitate the change in the production facilities or vice versa. For instance, the apparel industry seasonally updates the design of the products which can be manufactured by the existing production system.

### *8.2.4 Step 1.4: Measuring resource efficiency during the manufacturing phase*

Based on the literature finding, most of the studies are mainly considered energy efficiency consideration. This research therefore aims to further improve the key resource efficiency (include material efficiency, energy efficiency and water efficiency) by identifying and improving P&PS hotspots which have the high resource consumption during the manufacturing operation phase. In this task, energy, water and materials which are generally consumed during production are assessed, and the environmental impacts which has been considered are a type of material use (scarcity material), mass of material consumption, ratio of material waste, ratio of recycle shipped and scrap, a volume of water consumption, renewable water, wastewater, greywater, ratio of renewable energy used, energy use for maintain working environment, energy used for material handling. The assessment of resources can be conducted following the research produced at the Centre for SMART (Sustainable Manufacturing and Recycling Technology) as follows:

i. The framework for Material Flow Assessment (MFAM) (Gould and Colwill 2015)
ii. Water usage Efficiency Ratios (WER) (Sachidananda *et al.* 2016)
iii. The framework for modelling Embodied Product Energy (EPE) (Seow *et al.* 2013)

In this light, the production hotspots which have high energy consumption, produce significant amounts of contaminated water or material waste can be marked through a production process hotspot identification workflow (see Figure 8.4). This is comprised of production system modelling and resource consumption assessment via the MFAM, WER and EPE frameworks. Current production process flows must be modelled to systematically identify qualitative and quantitative information regarding material, water, and energy for resource assessment.

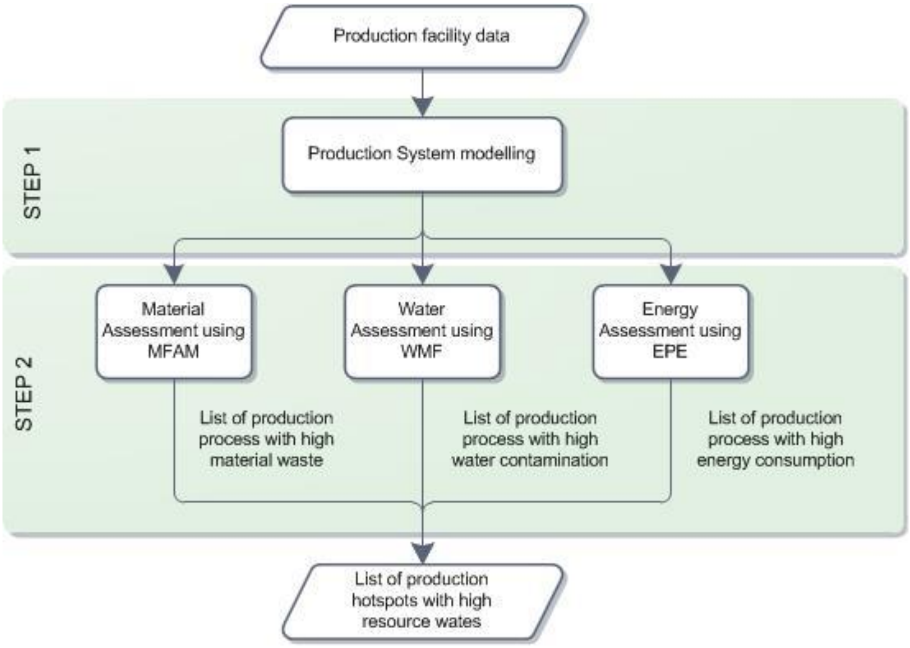


*Figure 8.4 – A workflow of Critical resource identification*

Manufacturing companies which already document this information may skip this step and directly start resource consumption assessment.

### *8.2.4.1 Material Consumption Assessment*

Material consumption and material waste in manufacturing industries can be identified in Phases 1 - 3 of the framework for material flow assessment in manufacturing systems (MFAM) (Gould & Colwill, 2015), as shown in Figure 8.5. This framework begins with the production system scope, which can directly be carried over from the modelled production system determined previously. Then, material flow can be assembled via qualitative and quantitative data inputs. Qualitative data includes a list of embedded materials (materials which are embedded into the final product), auxiliary material (material required in the production system), and material information (key ingredients, hazard information, storage information, information related waste management and environmental impact), and the functions of each production process.

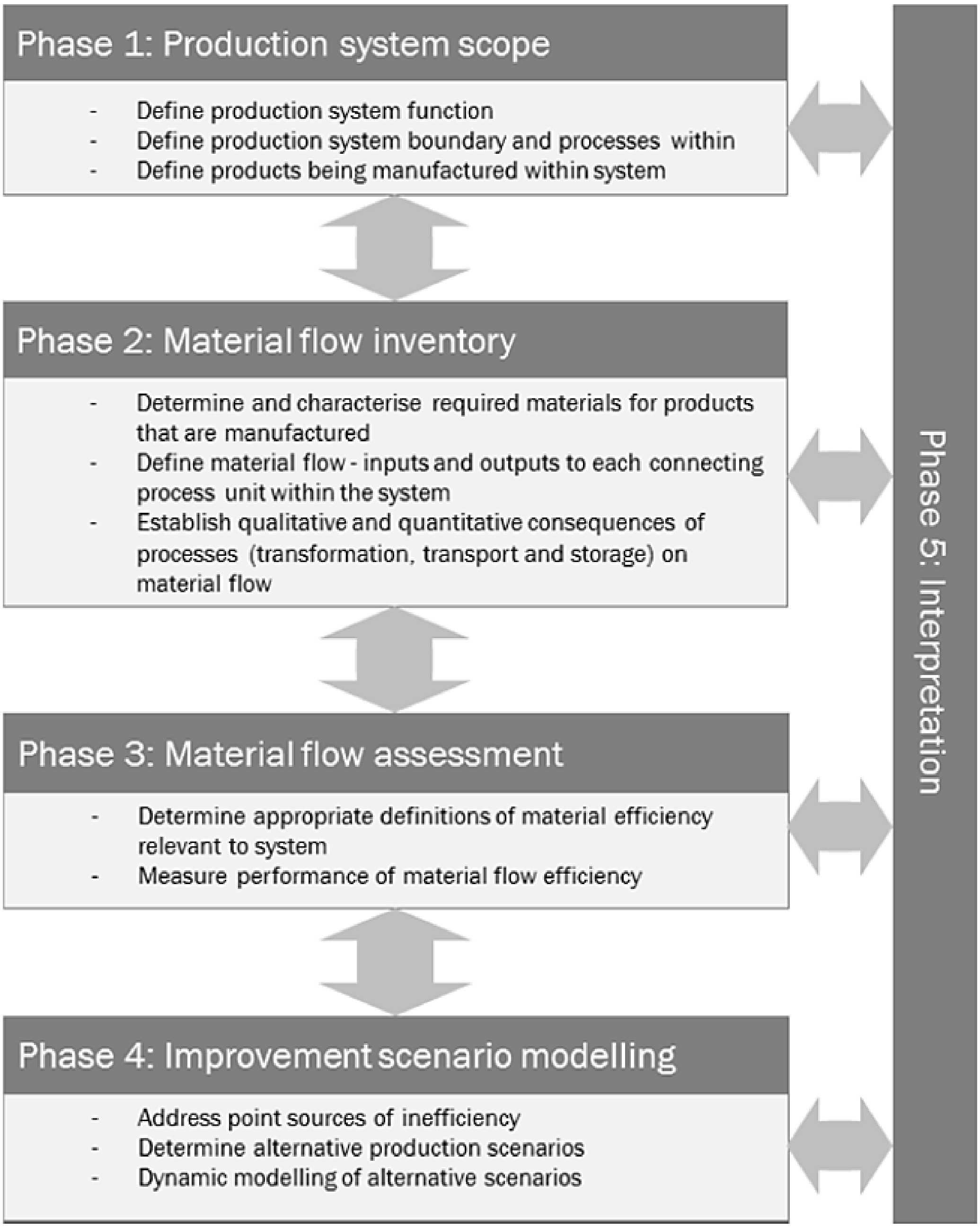


*Figure 8.5 - The framework for material flow assessment in manufacturing (MFAM)* (Gould and Colwill 2015)

Significant quantitative data consists of the material consumption rate (based on the information provided in bills of material), the economic value of the material (considering the value added from material transformation). With this material flow, selected metrics such as production yield loss in Phase 3 can be assessed, and the amount of waste along this flow can be presented to highlight opportunities for improving material efficiency. Subsequently, the critical material production processes can be conveyed by implementing MFAM from Phases 1-3.

### *8.2.4.2 Water consumption assessment*

The concept of Water usage Efficiency Ratio (WER) provides a systematic measurement of water consumption at the factory level, considering the amount of water used in each process and production system (Sachidananda *et al.* 2016). This concept categorises water use in a factory as shown in Figure 8.6. Factory water can be classified into two main types; Production Water (PDW) and Non-Production Water (NPW). PDW can further be categorised as Consumed water (C), Discharged Non-Renewable water (DNR), and Discharged Renewable Water (DRW). Process Water (PW) and System Water (SW) are two additional categories. With this classification, the WER can be mainly determined based on Water Intensity (WI) and the Waste Water Efficiency (WWE). The WI ratio was proposed to determine which processes use the largest proportions of water in a production system, while WWE is meant to identify the proportion of reusable wastewater to total water input. These two ratios can be determined as shown in the following equations;

Equation 8.2 $$WI_i = \frac{\sum PDW - PDW_i}{\sum PDW}$$

Equation 8.3 $$WWE_i = \frac{PDW_i - DNR_i}{PDW_i}$$

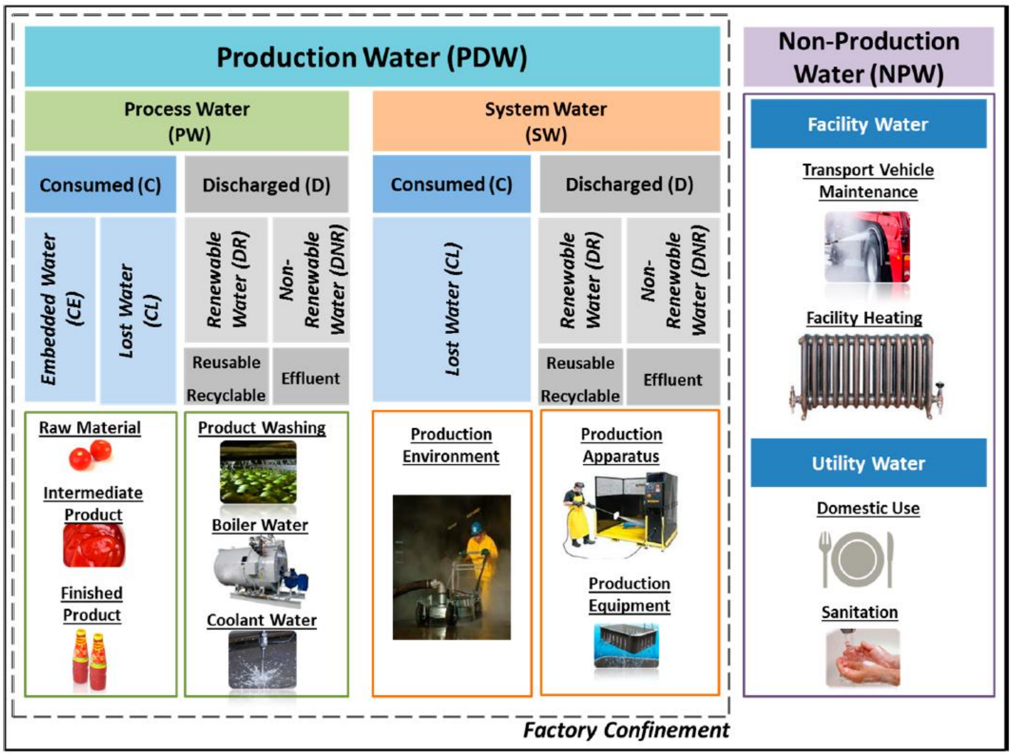


*Figure 8.6 - Factory Water classification scheme for manufacturing plants* (Sachidananda *et al.* 2016)

### *8.2.4.3 Energy Consumption Assessment*

The critical energy production process can be identified through a framework for modelling Embodied Product Energy (EPE), as shown in Figure 8.7. Within this framework, the energy consumption for producing a product is modelled on the product, production process and factory level. The energy used can be categorised into two main types: Direct Energy (DE) required for producing a product and Indirect Energy (IE) required to facilitate an environment for operating the production system. In greater detail, DE is further decomposed into Theoretical Energy (TE) consumed to transform a product, and Auxiliary Energy (AE) used to support production processes such as the coolant pumping process. With this qualitative energy and process information, the model of EPE is further quantified with mathematical models and system specifications. Therefore, energy assessment can be conducted through the calculation of process Efficiency Ratio (= TE/DE) and an energy efficiency production system (= DE/IE) to distinguish the energy hotspots of each product unit.

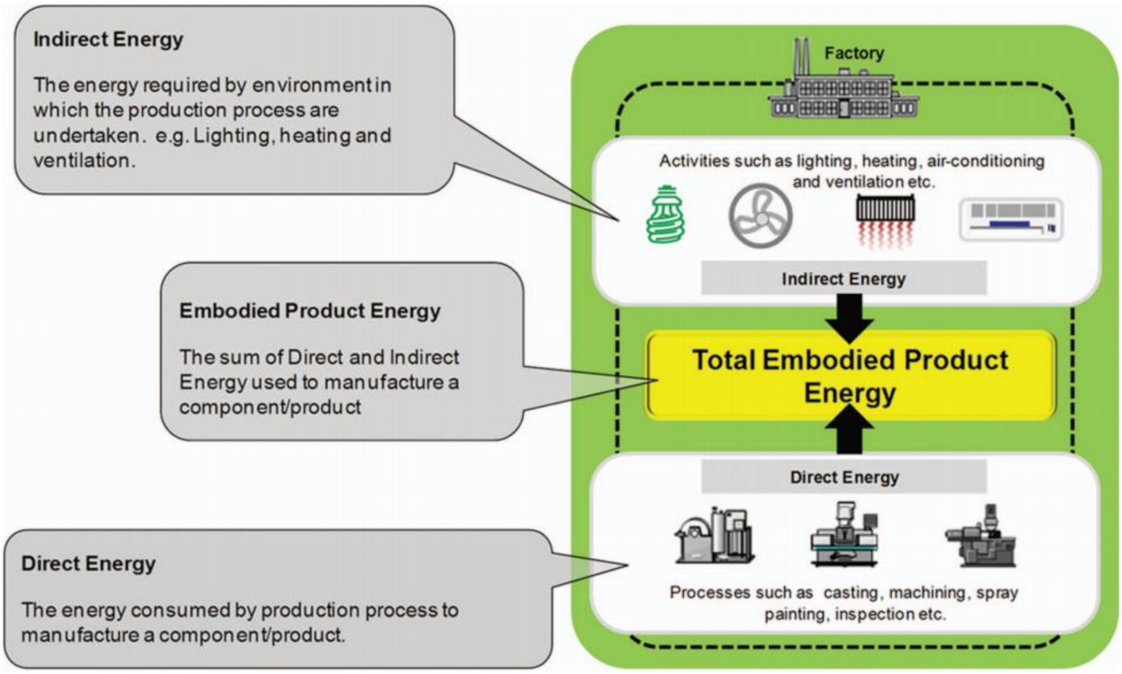


*Figure 8.7 - EPE framework consisting of Indirect Energy and Direct Energy (Seow et al. 2013)*

### *8.2.5 Step 1.5: Identifying the candidates for P&PS co-design processes*

Based on the results of the assessment from previous steps, this section provides a table for supporting decisions regarding the adoption of a new single P&PS co-design process. Fundamentally, this new co-design process is required if a manufacturing company which continuously updates product design, has a high level of P&PS interrelation and has intensive resource consumption. Based on this consideration, Table 8.3 suggests that a co-design process should be adopted only when product design is often updated and directly affects production system changes and when resource consumption of the production system is high or exceed the assigned threshold.

In summary, the analysis of the frequency of design change and consideration of resource efficiency in this initial phase will define the suitability of a co-design process adoption. The output of this is the existence of a group of P&PS which are suitable to be designed in a co-design process. At this phase of the framework, a decision could be made where Co-design is found to be not suitable and thus processing to the second phase stops. Otherwise, the steps in phase two are undertaken to assess an interrelation of design processes in order to decide the best strategy for Co-design as describe below.

*Table 8.3 - Classification table supporting decisions in Co-design implementation*

| PDU RATE | INTERRELATION OF P&PS UPDATE | RESOURCE EFFICIENCY | RECOMMEND DESIGN PROCESS |
|---|---|---|---|
| Low (PDU≤0) | FPSD ≠ FPD | High | Independent design |
| Low (PDU≤0) | FPSD ≠ FPD | **Low** | Independent design |
| Low (PDU≤0) | **FPSD = FPD** | High | Independent design |
| Low (PDU≤0) | **FPSD = FPD** | **Low** | Independent design |
| **High (PDU>0)** | FPSD ≠ FPD | High | Independent design |
| **High (PDU>0)** | FPSD ≠ FPD | **Low** | Independent design |
| **High (PDU>0)** | **FPS = FPD** | High | Independent design |
| **High (PDU>0)** | **FPS = FPD** | **Low** | **Co-design** |

## 8.3 PHASE 2: CO-SPECIFY PHASE

The Co-specify phase has three primary objectives, namely a) to identify design decisions which significantly impact resource consumption during the manufacturing phase, b) to define the interrelations P&PS design decisions, and c) to recommend the most suitable strategy for implementation of a single co-design process within a company, as presented in Figure 8.8.

In a case of a complex product, the relationship between various parts and components needs to be examined firstly, because any changes to one part and/or component design could impact not only the design of its production system but also the design of production processes for other related parts. Furthermore, in an application with simple products where various products share the same standard design process, the relationship between P&PS design processes should be assessed separately for products that do not share the same production system (see Figure 8.9). This is because these products may require a different amount of resource consumption, resulting in a different ecological impact. However, the main outputs from this phase for both complex and simple products are the specification for P&PS design decisions, and a recommendation for a suitable strategy for implementation of the co-design process, as described in the following sections.

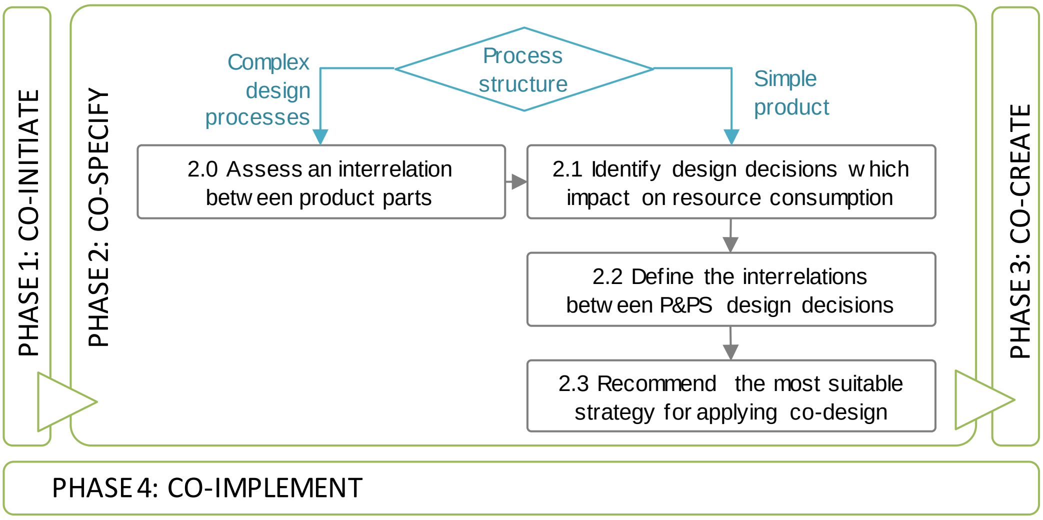


*Figure 8.8 - Overview of activities in the Co-specify phase*

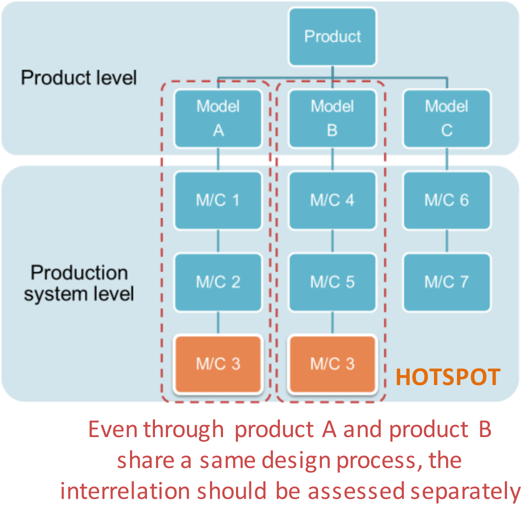


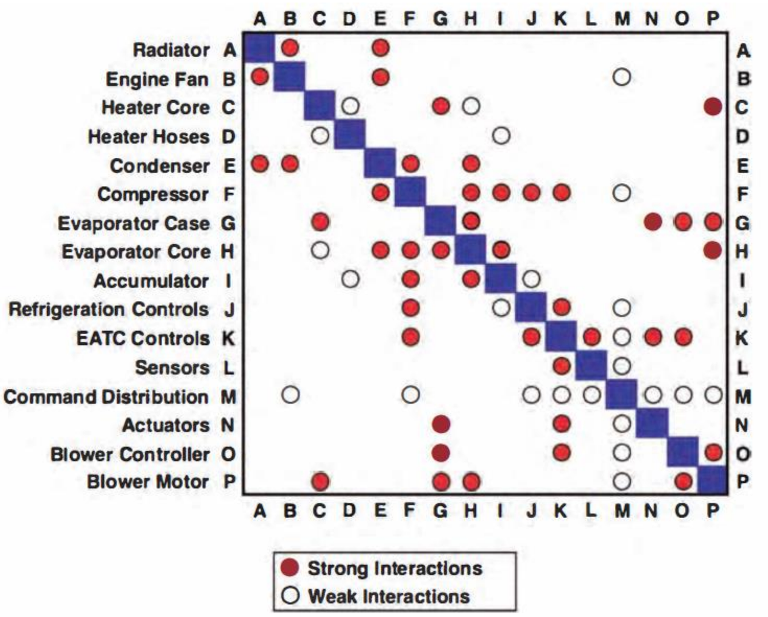
*Figure 8.9 - Differences of interrelation assessment based on the difference of production system*

### *8.3.1 Step 2.0: The interrelation between parts for a complex product*

For a complex product, a P&PS co-design process could be required only for some parts and their production systems (e.g. a subset of components within a vehicle). However, any changes or improvements in a part design for reducing resource consumption might result in a number of consequential changes in other related parts. For example, in a case of automotive seat design, a design change of a rear seatback can affect a change of a car body because these two parts are interfaced and interacted through fixing components and fixing-folding function. In such cases, the co-design of a complex product is limited by the interrelations of its parts. Therefore, a product architecture based on the DSM model (Eppinger and Browning 2012) is suggested to identify such interrelations, as presented in Figure 8.10. The results of this interrelation mapping can be used as input information to the next step in the P&PS co-design process.

### *8.3.2 Step 2.1: Identifying design decision which impacts on resource consumption*

Since not all P&PS design decisions have a similar impact on resource consumption, this step therefore identifies which design decisions have an impact on resource consumption and resource efficiency improvement. To complete this, the co-design operator is advised to document all design decisions of the P&PS candidates (defined from the previous phase) then identify these decisions regarding the resource efficiency improvement (based on the result of the resource consumption assessment). These two activities can be done through the step-by-step guide described in the following sub-sections.



| | | A | B | C | D | E | F | G | H | I | J | K | L | M | N | O | P | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Radiator | A | ■ | ● | | | ● | | | | | | | | | | | | A |
| Engine Fan | B | ● | ■ | | | ● | | | | | | | | ○ | | | | B |
| Heater Core | C | | | ■ | ○ | | | ● | ○ | | | | | | | | ● | C |
| Heater Hoses | D | | | ○ | ■ | | | | | ○ | | | | | | | | D |
| Condenser | E | ● | ● | | | ■ | ● | | ● | | | | | | | | | E |
| Compressor | F | | | | | ● | ■ | | ● | ● | ● | ● | | ○ | | | | F |
| Evaporator Case | G | | | ● | | | | ■ | ● | | | | | | ● | ● | ● | G |
| Evaporator Core | H | | | ○ | | ● | ● | ● | ■ | ● | | | | | | | ● | H |
| Accumulator | I | | | | ○ | | ● | | ● | ■ | ○ | | | | | | | I |
| Refrigeration Controls | J | | | | | | ● | | | ○ | ■ | ● | | ○ | | | | J |
| EATC Controls | K | | | | | | ● | | | | ● | ■ | ● | ○ | ● | ● | | K |
| Sensors | L | | | | | | | | | | | ● | ■ | ○ | | | | L |
| Command Distribution | M | | ○ | | | | ○ | | | | ○ | ○ | ○ | ■ | ○ | ○ | ○ | M |
| Actuators | N | | | | | | | ● | | | | ● | | ○ | ■ | | | N |
| Blower Controller | O | | | | | | | ● | | | | ● | | ○ | | ■ | ● | O |
| Blower Motor | P | | | ● | | | | ● | ● | | | | | ○ | | ● | ■ | P |
| | | A | B | C | D | E | F | G | H | I | J | K | L | M | N | O | P | |

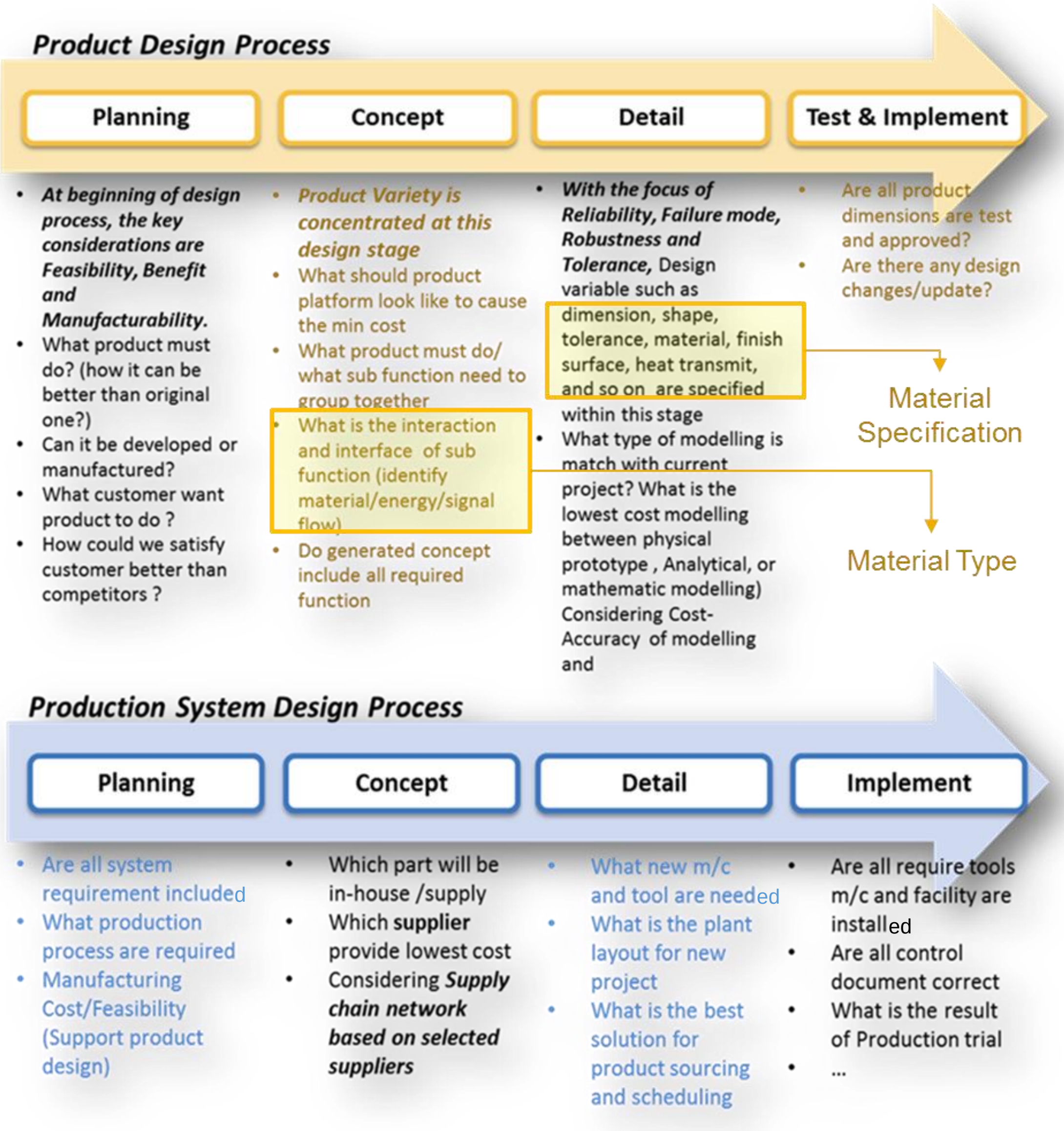
● Strong Interactions
○ Weak Interactions

*Figure 8.10 - An example of part interrelation assessment* (Eppinger and Browning 2012)

#### *8.3.2.1 Step 2.1.1: Modelling P&PS design processes and allocating design decisions and specification*

To prepare a design process assessment, all design decisions should be identified through modelling current design processes. Particularly, a design process is typically presented as an activity process flow transforming and delivering qualitative and quantitative information. The required design information includes design stages, product design activities, design decisions, input and output data of the design stages, and all related operators of design stages. This step of design process modelling can be conducted using existing functional modelling methods, e.g. Functional Flow Block Diagram, Design structure analysis, IDEF3, IDEF0 or axiomatic design.

Typically, a list of design specifications is already recognised in the existing design process. However, this step of design specification listing is created to confirm that all design specification is included in the consideration. In Figure 8.11, examples of significant product design specifications include geometry, materials, signals, energy, safety, ergonomics, aesthetics, cost, quality, timescale, environment, maintenance, regulation/legislation, and transportation. Similarly, examples of significant production system design specifications are production process/machine type (fabricate/assembly), technology, the number of machines, production capacity, plant rate, process flow, material flow, production planning, plant layout, material handling equipment, installation, work organisation and environment, and ergonomics.



m/c: machine

*Figure 8.11 - Examples of design decision allocation in P&PS design processes*

With a conventional design process, some design specifications have not been finalised during a single design step. For instance, the material of a product is considered at two design stages. One type of material is firstly decided at an early design stage, then another material type and its specification are finalised at a more detailed design stage. Hence, P&PS design specifications should be defined at the level of design decisions (a sub-specification), as shown in Figure 8.12.

Based on the literature findings, many design companies do not have a formal or structured design process, especially when designing something simple. Therefore, a design specification allocation checklist is proposed to support the allocation of design decisions and organise a formal design process.

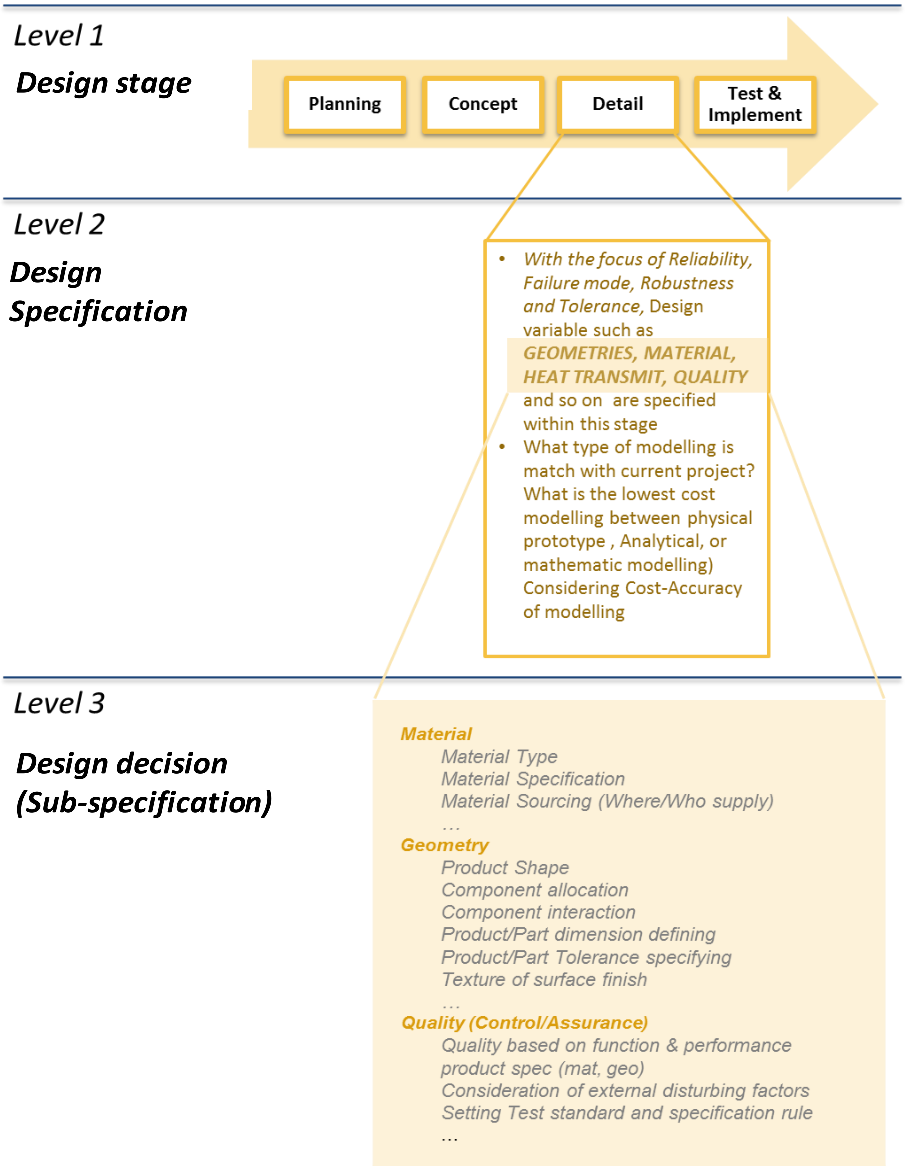
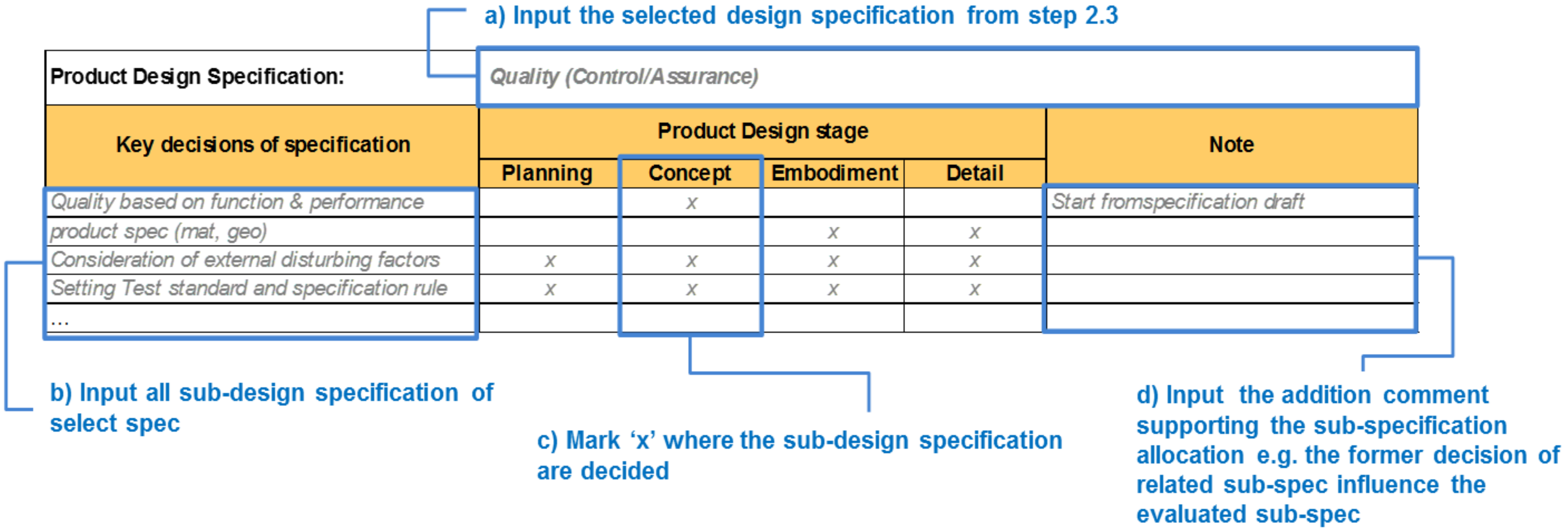


*Figure 8.12 - Three levels of design information*

Product and production system designers are requested to confirm where each design decision is decided. In Table 8.4, this checklist requires the input of data, such as a) design decisions (sub-design specifications), b) the location of sub-design specifications, and c) additional information relating to design decisions (sub-design specifications). This design decision allocation can support P&PS interrelation assessment and the creation of a single co-design process during the next Co-create phase.  Nevertheless, if the company already has a developed design process flow, this step of modelling might be excluded, and one would directly proceed to the following step.

*Table 8.4 - Detailed input data on a product design specification allocation check sheet*



a) Input the selected design specification from step 2.3

| **Product Design Specification:** | *Quality (Control/Assurance)* | | | | |
|---|---|---|---|---|---|
| **Key decisions of specification** | **Product Design stage** | | | | **Note** |
| | **Planning** | **Concept** | **Embodiment** | **Detail** | |
| *Quality based on function & performance* | | *x* | | | *Start fromspecification draft* |
| *product spec (mat, geo)* | | | *x* | *x* | |
| *Consideration of external disturbing factors* | *x* | *x* | *x* | *x* | |
| *Setting Test standard and specification rule* | *x* | *x* | *x* | *x* | |
| … | | | | | |

b) Input all sub-design specification of select spec

c) Mark ‘x’ where the sub-design specification are decided

d) Input the addition comment supporting the sub-specification allocation e.g. the former decision of related sub-spec influence the evaluated sub-spec

#### *8.3.2.2 Step 2.1.2: Identifying P&PS design decisions which impact on resource consumption*

The co-design operator can perform this ecological identification (Eco-identification) with the support of a resource-efficient expert. This step consists of two steps which are to select resource efficiency criteria based on the result of resource consumption and to classify a particular design specification as to whether it impacts resource efficiency or not.

First, based on the result of resource consumption for the Co-initiate phase, the co-design operator should select the applicable eco-strategy to be used as the ecological classification criteria. For example, footwear design, material and energy are assumed to be highly used during the manufacturing phase. Regarding the literature finding and the focus on improvement of resource efficiency, the potential SD strategies which may be applied to reduce the resource consumption is presented in Table 8.5 and 8.6. In a context of product design, sustainable design strategies cover material elimination (dematerialise product service and consolidate material variety), material minimisation (restructuring product, size reduction, light weighting and optimise the quantity of components), material substitution, material separation, energy minimisation, energy source substitution, water minimisation and wastewater treatment. For a production system consideration, sustainable design approaches are near net shape, waste in process minimisation, selection of low impact process, use of efficient packaging, adoption of a sustainable process, minimise operation, selection of renewable and safe energy source, shorten transportation distance, minimisation of wastewater, minimisation of grey/contaminated water and water recycling. In this case, it is assumed that there is high material waste during the cutting process and high energy consumption in the shoe-base injection process. Then, any SD approaches which can support the improvement of these resource efficiencies are selected as 'Y' in the 'improve PS candidate' column. In contrast, if the identified SD approaches are not suitable for this case, it should be marked as 'n' (not improve PS candidate). Then, the co-design operator should classify which PD and PSD specifications are required to consider in applying the selected SD approaches. This can be done through the design specification Eco-identification table as depicted in Table 8.7 and 8.8. In these tables, if a certain design specification (in a row) is required in operating the selected SD approach (in a column), this specification should be marked as 'X'. If it is not required, the box should be left blank. Then, the required design specification will be used for further interrelation assessment in the following steps.

*Table 8.5 – A selection of criteria for classifying product specification based on the result of resource consumption assessment*

| Applicable SD approaches for product | Please input 'Product/Component name' if a strategy is applicable | Improve PS candidate or not |
|---|---|---|
| **1. Material** | | |
| a. Material Elimination | | |
| i. Dematerialise product service | *n/a* | - |
| ii. Consolidate material variety (Homogenous material/Standardised component) | *Sport shoe* | *Y* |
| b. Material Minimisation | | |
| i. Restructuring product | *n/a* | - |
| ii. Size reduction (near net shape) | *Sport shoe* | *n* |
| iii. Light weighting | *Sport shoe* | *n* |
| iv. Optimise quantity of component | *Sport shoe* | *n* |
| c. Material Substitution | | |
| i. Optimise geometry | *Sport shoe* | *Y* |
| ii. Selection of recyclable materials | *Sport shoe* | *Y* |
| iii. Selection of reuse/remanufactured component | *n/a* | - |
| iv. Selection of low impact materials (non-toxic, responsible sourced) | *Sport shoe* | *n* |
| v. Consider material longevity and durability (corrosion resistant, appropriate to use life) | *Sport shoe* | *Y* |
| d. Material separation | | |
| i. Avoid coating/lamination | *Sport shoe* | *n* |
| ii. Limited use of adhesives | *Sport shoe* | *n* |
| **2. Energy** | | |
| a. Energy Minimisation | | |
| i. Energy efficiency during use (efficient mechanism and operation of product) | *n/a* | - |
| b. Energy source substitution | | |
| i. Considering energy type and source during use (from safe and renewable sources) | *n/a* | - |
| **3. Water** | | |
| a. Water Minimisation | | |
| i. Water efficiency during use (efficient mechanism and operation of product, reduce wastewater) | *n/a* | - |
| b. Wastewater treatment | | |
| i. Considering quality of discharge water after use | *n/a* | - |

*Table 8.6 – A selection of criteria for classifying production specification based on the result of resource consumption assessment*

| Applicable SD approaches for production system | Please input 'Product/Component name' if a strategy is applicable | Improve PS candidate or not |
|---|---|---|
| **1. Material** | | |
| a. Near net shape | *Sport shoe* | *Y* |
| b. Waste in process minimisation | *Sport shoe* | *Y* |
| c. Selection of process which produce low/zero waste | *Sport shoe* | *Y* |
| d. Efficient packaging (minimised packaging materials and volume of packages) | *Sport shoe* | *n* |
| e. Adoption of remanufacturing process, recycling process | *Sport shoe* | *Y* |
| f. Adoption of take back and collection methods | *Sport shoe* | *n* |
| **2. Energy** | | |
| a. Minimise operation (Eliminate unnecessary operation) | *Sport shoe* | *n* |
| b. Selection of process which consume less energy (energy efficiency in production process) | *Sport shoe* | *Y* |
| c. Selection of energy type and source used in production (safe and renewable source) | *Sport shoe* | *Y* |
| d. Transportation method | *Sport shoe* | *n* |
| e. Geographical location of manufacturing, operations and suppliers (Shortening Distance of transportation) | *n/a* | - |
| **3. Water** | | |
| a. Waste water minimisation | *n/a* | - |
| b. Contaminated/Grey water minimisation | *n/a* | - |
| c. Water recycling | *n/a* | - |

*Table 8.7 – An example of 'Ecological identification' of PD specifications*

| Product Design | | MATERIAL | | | |
|---|---|---|---|---|---|
| | | Elimination | Substitution | | |
| no. | Decision | ii. Consolidate material variety (Homogenous material/Standardised component) | i. Optimise geometry | ii. Selection of recyclable materials | v. Consider material longevity and durability (corrosion resistant, appropriate to use life) |
| 1 | Geometry | | *x* | | |
| 2 | Material type | *x* | | *x* | *x* |
| 3 | Material specification and property | *x* | | *x* | *x* |
| 4 | Product shape | *x* | *x* | | |
| 5 | Component allocation | *x* | *x* | | |
| 6 | Component interaction | *x* | *x* | | |
| 7 | Product/Part dimension defining | | *x* | | |
| 8 | Product /Part tolerance specifying | | *x* | | |
| 9 | Aesthetics | *x* | *x* | *x* | *x* |
| 10 | Texture of finished surface | *x* | | *x* | |
| 11 | Signal | | | | |
| 12 | Energy | | | | |
| 13 | Safety | *x* | | *x* | *x* |
| 14 | Ergonomics | *x* | | *x* | *x* |
| 15 | Quality | *x* | *x* | *x* | *x* |
| 16 | Durabiltiy | *x* | | *x* | *x* |

*Table 8.8 – An example of 'Ecological identification' of PSD specifications*

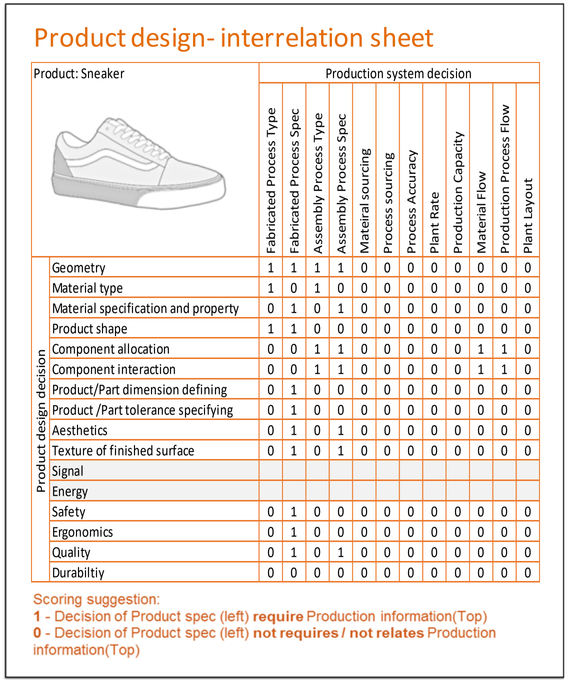
| **Production System Design** | | **MATERIAL** | | | | **ENERGY** | |
|---|---|---|---|---|---|---|---|
| no. | Decision | a. Near net shape | b. Waste in process minimisation | c. Selection of process which produce low/zero waste | e. Adoption of remanufacturing process, recycling process | b. Selection of process which consume less energy (energy efficiency in production process) | c. Selection of energy type and source used in production (safe and renewable source) |
| 1 | Fabricated Process Type | x | x | x | | x | |
| 2 | Fabricated Process Specification | x | x | x | | x | |
| 3 | Assembly Process Type | | x | x | | x | |
| 4 | Assembly Process Specification | | x | x | | x | |
| 5 | Mateiral sourcing | | | | | | |
| 6 | Process sourcing | | | x | x | x | |
| 7 | Process Accuracy | | | | | | |
| 8 | Plant Rate | | | | | | |
| 9 | Production Capacity | | | x | x | x | x |
| 10 | Material Flow | | | | | | |
| 11 | Production Process Flow | | x | x | x | x | x |
| 12 | Plant Layout | | x | x | x | x | x |

### *8.3.3 Step 2.2: Assessing the interrelation between design decisions in P&PS*

An assessment of how P&PS design decisions interrelate can be processed based on the classification of task relationships mentioned in Chapter 5. Therefore, this step provides a two-step approach guiding designers to classify the interrelation of P&PS and arrive at a co-design specification. These are detailed in the following sub-steps.

#### *8.3.3.1 Step 2.2.1: Assessing the interrelation between P&PS design decisions*

At this step, the co-design operator can prepare an assessment of the interrelation between P&PS design decisions using information provided from a previous step. In Figure 8.13, a list of P&PS design decisions is recorded into a co-design interrelation assessment sheet, which is adapted from the Domain Mapping Matrix (Danilovic and Browning 2007). Two forms of checklists are provided; they differ regarding the purpose of use and required input data, as presented in Figure 8.13 (a) and (b). In the first format, product designers will be requested to score the decision of a single design spec as:



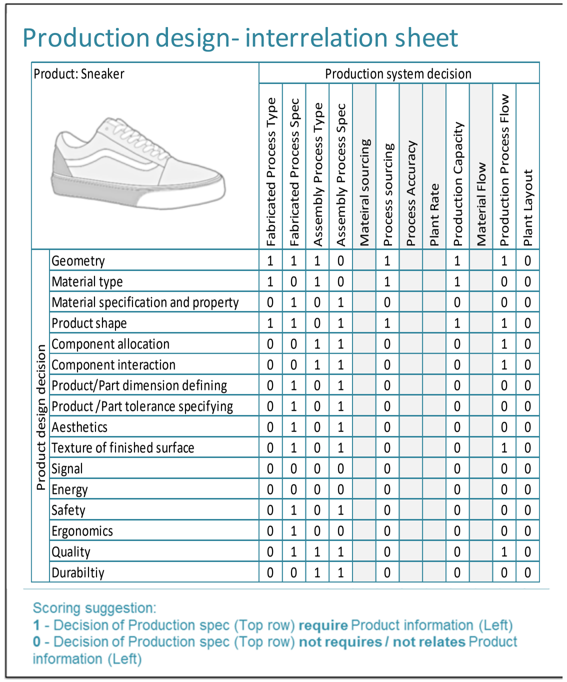
Product design- interrelation sheet

| Product: Sneaker | | Production system decision | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Fabricated Process Type | Fabricated Process Spec | Assembly Process Type | Assembly Process Spec | Mateiral sourcing | Process sourcing | Process Accuracy | Plant Rate | Production Capacity | Material Flow | Production Process Flow | Plant Layout |
| Product design decision | Geometry | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Material type | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Material specification and property | 0 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Product shape | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Component allocation | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 |
| | Component interaction | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 |
| | Product/Part dimension defining | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Product /Part tolerance specifying | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Aesthetics | 0 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Texture of finished surface | 0 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Signal | | | | | | | | | | | | |
| | Energy | | | | | | | | | | | | |
| | Safety | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Ergonomics | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Quality | 0 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Durabiltiy | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

Scoring suggestion:
**1** - Decision of Product spec (left) **require** Production information(Top)
**0** - Decision of Product spec (left) **not requires / not relates** Production information(Top)

A product designer will identify whether the availability of information related a production system spec is useful to support an ecological decision of a particular product spec or not

*Figure 8.13(a) - Interrelation check sheets for a product designer*



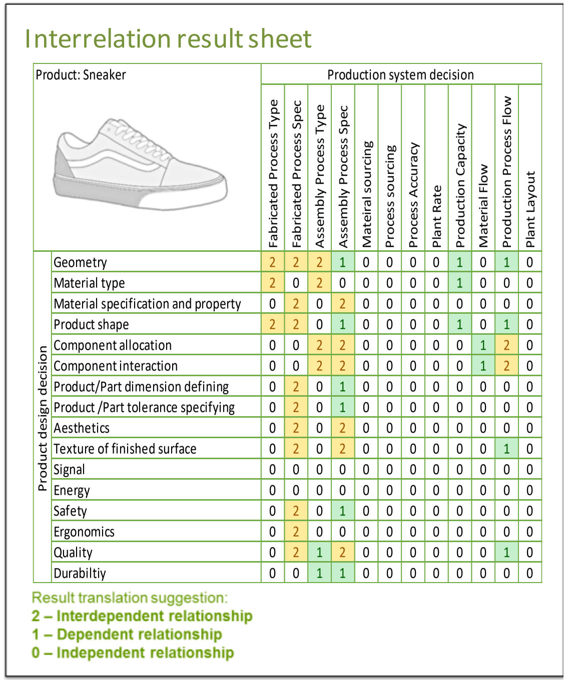
Production design- interrelation sheet

| Product: Sneaker | | Production system decision | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Fabricated Process Type | Fabricated Process Spec | Assembly Process Type | Assembly Process Spec | Mateiral sourcing | Process sourcing | Process Accuracy | Plant Rate | Production Capacity | Material Flow | Production Process Flow | Plant Layout |
| Product design decision | Geometry | 1 | 1 | 1 | 0 | | 1 | | | 1 | | 1 | 0 |
| | Material type | 1 | 0 | 1 | 0 | | 1 | | | 1 | | 0 | 0 |
| | Material specification and property | 0 | 1 | 0 | 1 | | 0 | | | 0 | | 0 | 0 |
| | Product shape | 1 | 1 | 0 | 1 | | 1 | | | 1 | | 1 | 0 |
| | Component allocation | 0 | 0 | 1 | 1 | | 0 | | | 0 | | 1 | 0 |
| | Component interaction | 0 | 0 | 1 | 1 | | 0 | | | 0 | | 1 | 0 |
| | Product/Part dimension defining | 0 | 1 | 0 | 1 | | 0 | | | 0 | | 0 | 0 |
| | Product /Part tolerance specifying | 0 | 1 | 0 | 1 | | 0 | | | 0 | | 0 | 0 |
| | Aesthetics | 0 | 1 | 0 | 1 | | 0 | | | 0 | | 0 | 0 |
| | Texture of finished surface | 0 | 1 | 0 | 1 | | 0 | | | 0 | | 1 | 0 |
| | Signal | 0 | 0 | 0 | 0 | | 0 | | | 0 | | 0 | 0 |
| | Energy | 0 | 0 | 0 | 0 | | 0 | | | 0 | | 0 | 0 |
| | Safety | 0 | 1 | 0 | 1 | | 0 | | | 0 | | 0 | 0 |
| | Ergonomics | 0 | 1 | 0 | 0 | | 0 | | | 0 | | 0 | 0 |
| | Quality | 0 | 1 | 1 | 1 | | 0 | | | 0 | | 1 | 0 |
| | Durabiltiy | 0 | 0 | 1 | 1 | | 0 | | | 0 | | 0 | 0 |

Scoring suggestion:
**1** - Decision of Production spec (Top row) **require** Product information (Left)
**0** - Decision of Production spec (Top row) **not requires / not relates** Product information (Left)

A production system designer will identify whether the availability of information related a product spec is useful to support an ecological decision of a particular production system spec or not

*Figure 8.13(b) - Interrelation check sheets for a production system designer*



Interrelation result sheet

| Product: Sneaker | | Production system decision | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Fabricated Process Type | Fabricated Process Spec | Assembly Process Type | Assembly Process Spec | Mateiral sourcing | Process sourcing | Process Accuracy | Plant Rate | Production Capacity | Material Flow | Production Process Flow | Plant Layout |
| Product design decision | Geometry | 2 | 2 | 2 | 1 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 0 |
| | Material type | 2 | 0 | 2 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 |
| | Material specification and property | 0 | 2 | 0 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Product shape | 2 | 2 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 0 |
| | Component allocation | 0 | 0 | 2 | 2 | 0 | 0 | 0 | 0 | 0 | 1 | 2 | 0 |
| | Component interaction | 0 | 0 | 2 | 2 | 0 | 0 | 0 | 0 | 0 | 1 | 2 | 0 |
| | Product/Part dimension defining | 0 | 2 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Product /Part tolerance specifying | 0 | 2 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Aesthetics | 0 | 2 | 0 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Texture of finished surface | 0 | 2 | 0 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 |
| | Signal | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Energy | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Safety | 0 | 2 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Ergonomics | 0 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Quality | 0 | 2 | 1 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 |
| | Durabiltiy | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

Result translation suggestion:
**2 – Interdependent relationship**
**1 – Dependent relationship**
**0 – Independent relationship**

A co-design person in charge will combine the results from the filled check sheet to classify an interrelation of each pair of product and production system specification

*Figure 8.13(c) - Interrelation check sheets for a co-design person in charge*

i. ‘0’ when the decision on the specific product design spec does not require information or knowledge support from the production system design
ii. ‘1’ when the decision on the specific product design spec requires information or knowledge support from the production system design.

On the other hand, another format of the PSD spec sheet is for the production system designer to input the requirements of product design knowledge or information in designing production systems with a similar pattern.

With the completed forms, the co-design operator will continue the analysis of interrelations by combining the results from the product and a production system forms. Such analysis results in a classification of P&PS interrelations, which are categorised into three main outcomes (See Figure 8.13(c)):

i. Value ‘0’: the two design decisions are independent
ii. Value ‘1’: one of the design decision depends on the other
iii. Value ‘2’: the two design decisions are interdependent

#### *8.3.3.2 Step 2.2.2: Determining co-design decisions and specifications*

Based on the results of the former step, this step involves specifying all design decisions assessed in the ecological classification and the P&PS interrelation assessment. The design decisions and specifications which do not impact resource consumption are also considered in this step. This is to conclude all design consideration to support the creation of a single co-design process. This step categorises design decisions (sub-specifications) into two categories:

i. ***An individual design decision*** which requires individual consideration from the product design team or production system design team, resulting from the P&PS interrelation of ‘0 - independent relationship’.
ii. ***A Co-design specification*** which requires co-consideration from the P&PS designers, resulting from the P&PS interrelation of ‘1 - dependent relationship’ or ‘2 - interdependent relationship’.

With the results from the case of footwear design in the previous step, the design specifications which are assigned to be co-designed are listed in Table 8.9 and 8.10. As the result of the design specification types, several stages of the product design and production system design need to be linked (see Figure 8.14) to create the coordinated design of P&PS according to specifications.

*Table 8.9 - An example of categorisation of footwear design specification*

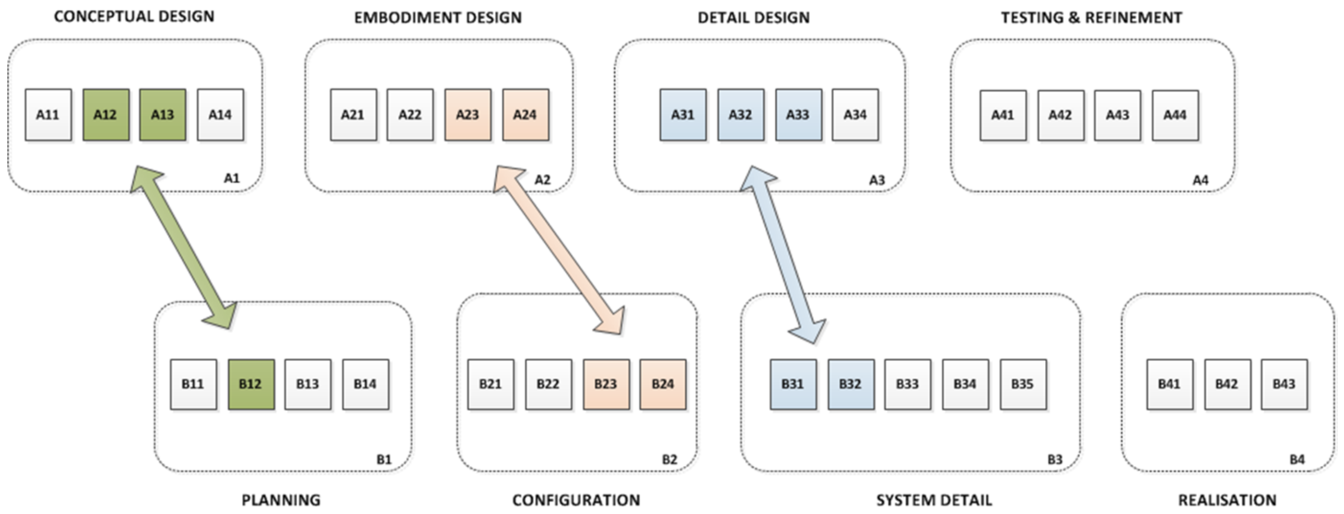
**Product Design Process**

| Design stage | Level of information | Design specification | Design Decision | Result of the interrelation assessment |
|---|---|---|---|---|
| Planning | 2 | patents | | An individual design decision |
| | 2 | product quantity | | An individual design decision |
| | 2 | product lifespan | | An individual design decision |
| | 2 | product service life | | An individual design decision |
| | 2 | product cost | | An individual design decision |
| | 2 | time scale | | An individual design decision |
| | 2 | customer | | An individual design decision |
| | 2 | company constraint | | An individual design decision |
| | 2 | manufacturing facility | | An individual design decision |
| | 2 | politics | | An individual design decision |
| | 2 | market constraint | | An individual design decision |
| | 2 | competitiion | | An individual design decision |
| | 2 | legislation | | An individual design decision |
| Conceptual design | 2 | environment | | An individual design decision |
| | 2 | materials | | A Co-design specification |
| | 3 | | material type | A Co-design specification |
| | 2 | geometry | | A Co-design specification |
| | 3 | | product shape | A Co-design specification |
| | 3 | | product size | A Co-design specification |
| | 3 | | product weight | A Co-design specification |
| | 3 | | geometric layout | A Co-design specification |
| | 3 | | component connection | A Co-design specification |
| | 2 | ergonomics | | An individual design decision |
| | 2 | performance | | An individual design decision |
| | 2 | documentation | | An individual design decision |
| Detail design | 2 | materials | | A Co-design specification |
| | 3 | | material property | A Co-design specification |
| | 3 | | material specification | A Co-design specification |
| | 3 | | material testing | An individual design decision |
| | 3 | | material sourcing | An individual design decision |
| | 2 | geometry | | A Co-design specification |
| | 3 | | product size (final) | A Co-design specification |
| | 3 | | product weight (final) | A Co-design specification |
| | 3 | | appearance finish | A Co-design specification |
| | 3 | | product and part dimension | A Co-design specification |
| | 3 | | product and part tolerance | A Co-design specification |
| | 3 | | texture of surface finish | A Co-design specification |
| | 3 | | aesthetics | An individual design decision |
| | 2 | quality | | A Co-design specification |
| | 3 | | reliability | A Co-design specification |
| | 3 | | durability | A Co-design specification |
| | 3 | | standard | An individual design decision |
| | 3 | | shelf life | An individual design decision |
| | 2 | product safety | | An individual design decision |
| | 3 | | setting test standard | An individual design decision |
| | 2 | product test | | An individual design decision |
| | 2 | shipping | | An individual design decision |
| | 2 | disposal | | An individual design decision |
| | 2 | packaging | | An individual design decision |
| | 2 | documentation | | An individual design decision |
| Test | 2 | testing | | An individual design decision |
| | 3 | | finalising test standard and specification | An individual design decision |
| | 2 | documentation | | An individual design decision |

*Table 8.10 - An example of categorisation of footwear production system specification*

**Production System Design Process**

| Design stage | Level of information | Design specification | Design Decision | Result of the interrelation assessment |
|---|---|---|---|---|
| Planning | 2 | product quantity | | An individual design decision |
| | 2 | production process | | An individual design decision |
| | 3 | | fabrication process type | A Co-design specification |
| | 3 | | assembly process type | A Co-design specification |
| | 2 | P&PS feasibility | | An individual design decision |
| | 2 | development time | | An individual design decision |
| | 3 | | plant rate | An individual design decision |
| | 3 | | takt time | An individual design decision |
| | 2 | capacity | | An individual design decision |
| | 2 | production volume | | An individual design decision |
| | 2 | product life cycle | | An individual design decision |
| Conceptual system | 3 | | make or buy decision | An individual design decision |
| | 2 | process flow sequencing | | A Co-design specification |
| | 3 | | operation sequence | A Co-design specification |
| | 2 | material and product flow | | A Co-design specification |
| | 3 | | buffer/ work in progress | An individual design decision |
| | 3 | | supplier selection | An individual design decision |
| Detail system | 2 | process flow sequencing | | An individual design decision |
| | 3 | | line balancing | An individual design decision |
| | 3 | | transport time | An individual design decision |
| | 3 | | queuing time | An individual design decision |
| | 2 | reliability | | An individual design decision |
| | 2 | inventory | | An individual design decision |
| | 3 | | space | An individual design decision |
| | 3 | | spare part | An individual design decision |
| | 3 | | store | An individual design decision |
| | 2 | production process | | A Co-design specification |
| | 3 | | fabrication process specification | A Co-design specification |
| | 3 | | fabrication process accuracy | A Co-design specification |
| | 3 | | assembly process specification | A Co-design specification |
| | 3 | | assembly process accuracy | A Co-design specification |
| | 3 | | workstation layout | An individual design decision |
| | 3 | | tolerance | An individual design decision |
| | 3 | | quantity of production processes | An individual design decision |
| | 2 | production layout | | An individual design decision |
| | 3 | | space | An individual design decision |
| | 2 | quality control | | A Co-design specification |
| | 2 | material handling equipment | | An individual design decision |
| | 2 | ergonomics | | An individual design decision |
| | 2 | maintenance | | An individual design decision |
| Production system realisation | 2 | system installation | | An individual design decision |
| | 2 | training | | An individual design decision |
| | 2 | work organisation | | An individual design decision |
| | 2 | work studies | | An individual design decision |
| | 2 | production safety | | An individual design decision |



**A1 Conceptual Design**
- A11 Customer requirement translation
- A12 Concept generation
- A13 Concept selection
- A14 Concept evaluation by customer

**A2 Embodiment Design**
- A21 Product decomposition
- A22 Component grouping
- A23 Allocate product part and draft and geometric
- A24 Interaction identification

**A3 Detail Design**
- A31 Refine geometry of product and parts
- A32 Material selection
- A33 Tolerance assignment
- A34 Industrial design refinement

**A4 Testing & Refinement**
- A41 Product performance testing
- A42 Regulation approval
- A43 Environmental impact assessment
- A44 Design improvement

**B1 Planning (System Requirement)**
- B11 Identify system requirement
- B12 Identify production process requirement
- B13 Estimate production cost
- B14 Production feasibility study

**B2 System Configuration**
- B21 Make or buy decision
- B22 Select key suppliers
- B23 Define process assembly scheme
- B24 Define high level process flow

**B3 System Detail Design**
- B31 Define production process
- B32 Design production process and set required quantity
- B33 Balance assembly line
- B34 Design plant layout
- B35 Production system simulation and evaluation

**B4 Testing & Refinement**
- B41 Production system installation
- B42 Production system trial
- B43 Production system refinement

*Figure 8.14 - An identification of co-design activities in footwear manufacturing based on the design decision*

### 8.3.4 Step 2.3: Recommendation for a suitable strategy for creating a single co-design process

Different manufacturing companies require a different level of P&PS design process improvement to achieve the potential benefit from P&PS co-design framework. Therefore, **3A strategy** is designed to fulfil the three different levels of co-design creation, which are temporary co-design, partial co-design, and full co-design through the ***A***wareness, ***A***ssociation, and ***A***daptation methods, respectively. This section therefore provides a Co-create guide for 3A strategy selection. This selection guide is based on two key factors, which are the simplicity or complexity of the product design process and the percentage of changes in PSD decisions, as presented in Table 8.11. In addition, the percentage of changes in PSD decisions can be determined based on a percentage of PSD that became the co-design specification. It has been asserted that the low level of product design update ($PDU < 0$) is expected to benefit less from the proposed P&PS co-design process. Therefore, a company which has low resource efficiency and high product design update ($PDU \geq 0$) can improve their design processes through this framework. In addition, a company which has a low number of co-decisions and applies a simple design process is suggested to set the co-design goal using the Awareness method. For a company with a high number of decisions in complex processes that require co-design considerations, establishing the co-design goal via the Adaptation method is recommended where Awareness and Association methods are completed first. For instance, in a case of footwear manufacturing, there is only 24% of PSD that developed Co-design decisions. Hence, it is suggested to apply co-design via the Awareness method since footwear is designed using the uncomplicated design processes by a small number of designers.

*Table 8.11 – 3A strategy selection guide based on product design update rate and co-decision ratio*

| CRITERIA FOR STRATEGY SELECTION | 3A STRATEGIES | | | |
|---|---|---|---|---|
| | Awareness | Association | | Adaptation |
| **Design process structure** | Simple process | Simple process | Complex process | Complex process |
| **Percentage of changes in PSD decision** | < 50% of PSD became Co-design decision | ≥ 50% of PSD became Co-design decision | < 50% of PSD became Co-design decision | ≥ 50% of PSD became Co-design Decision |

## 8.4 CHAPTER SUMMARY

This chapter has detailed the first two phases of the proposed P&PS co-design framework, in which these two phases provided step-by-step guidance for studying co-design feasibility and assessing the existing P&PS design processes. Three key considerations; the product design update rate, the interrelation between P&PS design updates, and the resource consumption of the production system, were used in the co-design feasibility study to identify potential benefits from co-design adoption in a given company. Also, two different approaches have been offered to determine the ecological interrelation of a simple product and a complex product and advise the suitable approach for co-design creation during the Co-specify phase.

The next chapter presents details of the activities that transform separated design processes into a single P&PS co-design process during the Co-create phase. Subsequently, the Co-implement phase will be further detailed in Chapter 10, with a demonstration of framework implementation using the available supporting tools while highlighting tools that require further development.

# CHAPTER 9 CO-CREATING A COMBINED PROCESS FOR DESIGNING PRODUCT AND PRODUCTION SYSTEM

## 9.1 INTRODUCTION

This chapter presents the third phase of the proposed framework, namely the Co-create phase which aims to provide a stepwise approach to construct a single process for designing P&PS to improve resource efficiency. An overview of this Co-create phase is given in Chapter 7. The main sections describe the details of the proposed '3A strategies' which offer three options for creating a new P&PS co-design process based on a number of considerations such as complexity of product design, the complexity of interrelation between P&PS designs, and potential complications in the co-design implementation.

## 9.2 PHASE 3: CO-CREATE PHASE

The first two phases of the framework focus on the evaluation of current design processes and specify how they should be improved. The third phase of the framework provides further guidance on how to create and implement a single P&PS co-design process. Due to significant variation in current design practices, this phase offers three specific strategies, referred to as **3*A* strategies** (see Figure 9.1), so that various manufacturing companies regardless of the frequency of their product updates, the resource efficiency of their production system and the interrelation between its P&PS design could construct a single co-design process which is tailored to their specific requirements.

Furthermore, these strategies could provide a gradual approach for the transition from the existing independent P&PS design processes into a single co-design process based on changes and improvements in design procedures, design knowledge management and performance of design collaborative. These strategies are briefly described below and detailly explained in the remaining sections of this chapter.

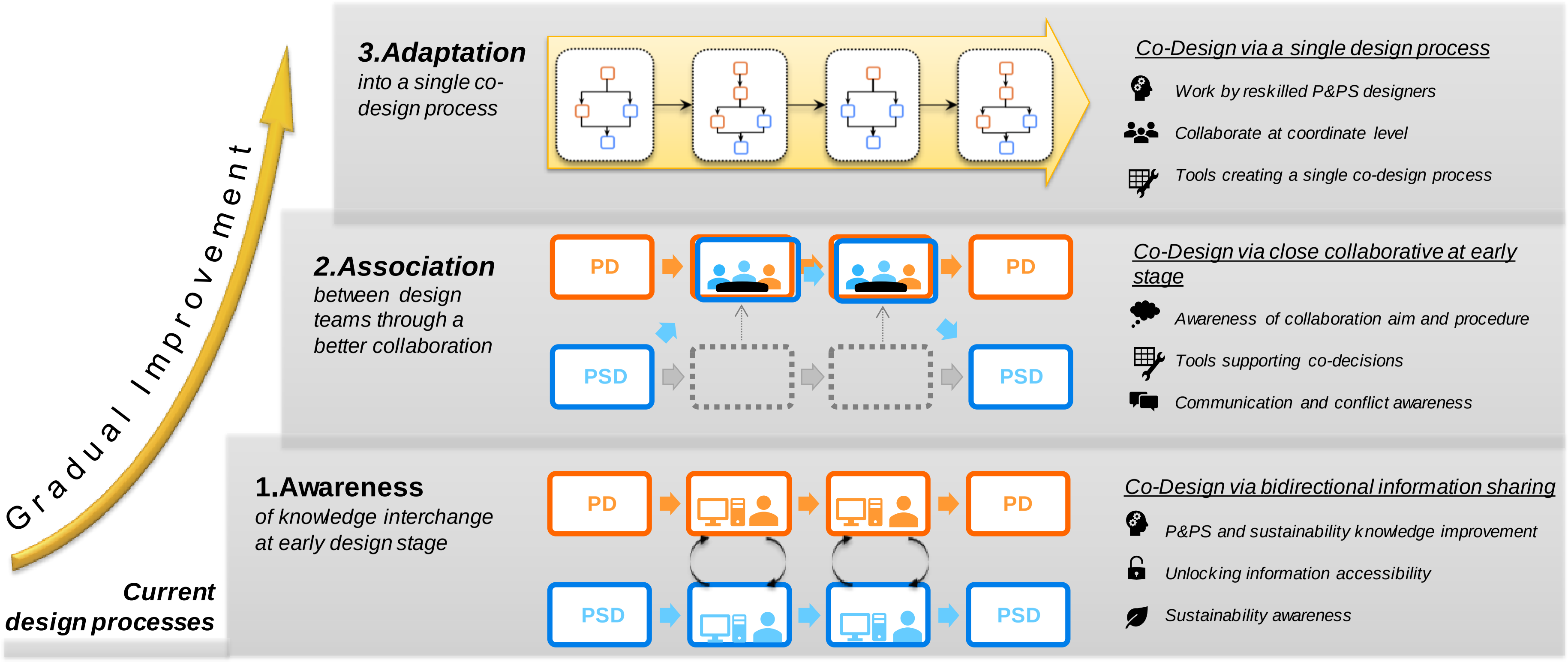


Figure 9.1 - The **3A strategies** for creating a P&PS co-design process

i. ***Awareness* of knowledge interchange**: This strategy aims to add targeted information exchange into the current design processes and improve knowledge sharing between P&PS co-design processes. To achieve this, a detailed understanding and mapping of information exchange and knowledge sharing among P&PS designers are necessary. In this strategy, the designers are provided with access to relevant and specific information and knowledge for improving the overall resource efficiency.

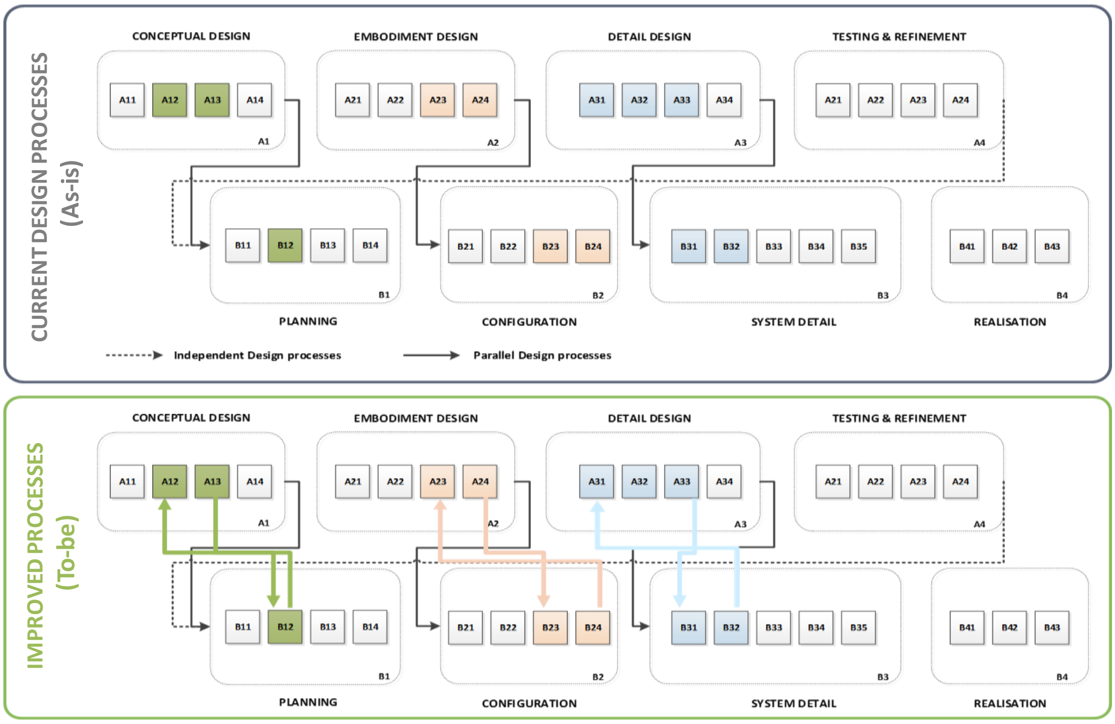
ii. ***Association* through closer collaboration between design teams:** In this strategy, a subset of design processes is modified based on close collaborative approach between product design and production system design teams (see Figure 9.1) because this strategy aims at the two cases. The first is where the targeted co-design decisions are more complex and require expertise from both design teams. Also, the applications in which the benefit of co-design P&PS is limited to a subset of design decisions, and the total transformation of existing independent design processes appears infeasible due to conflicts with legacy systems/procedures and potential costly operational changes.

iii. ***Adaptation* into a combined co-design process**: This strategy aims, where possible, to support a total transformation into a single combined design (co-design) in which this necessitates significant changes to current design practices including the need for reskilling of the P&PS co-designers who formerly were either product or production system designers. In this strategy, a Design Structure Matrix is used for rearranging the specified design decisions and activities for a concurrent approach to generating product and production system designs.

## 9.3 STRATEGY I: AWARENESS OF KNOWLEDGE AND INFORMATION INTERCHANGE

This first strategy is intended to support the application of co-design with low complexity of interrelations between product and production system design. In such cases, it is argued that an ‘**Awareness’** of information and knowledge interdependencies through a number of minor changes and improvements in design procedures could provide the majority of potential benefits expected from a P&PS co-design process.

The Awareness strategy, therefore, proposes organising co-design through **targeted and beneficial information and knowledge exchange**. In this approach, P&PS co-design activities can be generated by directly increasing information transfer and knowledge sharing between design processes, as well as incorporating ecological considerations. More specifically, product and production system designers are requested to increase communication to determine and refine the best solution for co-design specifications.  For example, in the case of footwear manufacturing (presented in Chapter 8), a shoe designer generally provides product design information to a shoe production system designer at the end of each stage in the design process using a unidirectional method. This implies that no feedback regarding the impact of this information on production system design is received by shoe designer (see ‘As-is’ diagram in Figure 9.2). In such cases, to achieve the benefit from a co-design approach, the design processes need to be arranged with additional ‘forward’ and ‘backward’ information exchange and knowledge sharing practices, as shown through the ‘To-be’ diagram in Figure 9.2.



| No. | Product Design | | Production system design | |
|---|---|---|---|---|
| | Consideration step | Specification | Specification | Consideration step |
| 1 | A12 – Concept generation<br>A13 – Concept Selection | Material type and Product Geometry | Fabricated and assembly process type | B12 – Identify production process requirement |
| 2 | A23 – Allocation product part and draft geometry<br>A24 – Interaction identification | Geometric layout and Component connection | Operation sequence and Material flow | B23 – Define process assembly scheme<br>B24 – Design high level process flow |
| 3 | A31 – Refine geometry of product and parts<br>A32 – Material specification selection<br>A33 – Tolerance assignment | Material property, Material specification, Refined geometry, and Product Quality | Fabricate and assembly process (specification and accuracy) and Quality control | B31 – Define production process<br>B32 – Design production process and required quantity |

*Figure 9.2 - Co-design by the Awareness of knowledge and information interchange*

In this context, it may seem that such additional information exchange and knowledge sharing might increase development time. However, in practices, this often results in a reduction of the development time as well as resource consumption due to more effective communication between design teams. Therefore, to effectively apply the Awareness strategy, there is a need a) to identify the targeted and beneficial information exchange and b) to improve the current practices for knowledge and information accessibility by P&PS designers.

### *9.3.1 Identifying the targeted and beneficial information exchange*

The various steps in Co-specify phase (see section 8.3) aid with identifying the need for additional ecological considerations and increase information transfers to ensure that the P&PS decisions lead to the improvements in resource efficiency during the production phase. This is initiated by developing an 'As-is' information flow in step 2.1 of Co-specify phase (see Section 8.3.2). Following this, the co-design interrelation assessment sheets (see Figure 8.13) that are generated in step 2.2 of co-specify phase to interact with product and production system designers, are utilised to identify the targeted and beneficial information exchange proposed by various designers. For example, in the design processes depicted in Figure 9.2 (based on footwear manufacturing application), three possible improvements in information exchange are proposed relating to:

i. Material type and product geometry with fabrication and assembly process pre-design in conceptual design,
ii. Geometric layout and component connection with material flow planning and operation sequencing in embodiment design, and
iii. Material property and specification, geometry refinement and product quality with fabrication and assembly process specification as well as the design of quality control process in detailed design.

To improve ecological considerations in this strategy, two additional design 'gates' are added to the co-design process. First, the information related to the available ecological options of product specification based on ecological considerations (e.g. material substitution) is shared with production system designers to assess the impact on their production system specifications. Then, the production system designers provide feedback regarding the production feasibility of these options to product designer before finalising the P&PS co-design decisions.

### *9.3.2 Improve the current practices for knowledge and information accessibility by P&PS designers*

To achieve this strategy, knowledge and information accessibility between product and production system designers should be improved through a) providing further training to P&PS designers, and b) adopting and incorporating proper knowledge and information management tools.

In view of further training, a product designer should be provided with additional knowledge related to the production system configuration through specially designed training course (and tools) as well as exchanging skills and experience with a production system designer. For example, a product designer should study basic steps involved in production system development, gaining sufficient technical knowledge on the production processes most related to their roles and responsibilities in product design. In the same way, production system designers should also receive further training on specific notation, terminology and technical language used in product design and development. More importantly, both sets of designers need to extend their knowledge of resource efficiency and sustainability considerations and practices within their company. This improvement can be achieved through the published assessment methods, such as the 'sustainability survey' introduced by Short *et al.* (2012).

In view of improving knowledge and information management tools, the relevant information related to resource-efficient design should be available and accessible to both P&PS designers. Availability of information is dependent on a manufacturing company's initiatives to collect and acquire relevant internal data (e.g. recyclability of materials used in the existing products, water and energy consumption rates at a production process level) as well as external information (e.g. emerging alternative low impact materials and/or resource-efficient technologies) related to resource-efficiency and environmental sustainability of their products and operations. The accessibility of information can be assessed by the specific capabilities of the information sharing tools (e.g. ability to keep information up-to-date, continuous monitoring and clear documentation, accessibility and contribution of information) employed by the manufacturing company. In this context, the range of possible capabilities of information sharing tools and its usage to support the collaboration activities can be classified into four levels of practice based on accessibility, modifiability, and authority, and information control, as identified by Prasad (1996):

Level i. Other users can only access information when the owner provides the accessibility.

Level ii. Multiple users can access information, which can be modified only by the owner.

Level iii. Multiple users can access and sequentially modify information, but they must request final approval from the owner.

Level iv. Multiple users can access in parallel and modify information; nonetheless, the modification requires approval by all related members.

While current information sharing tools within the majority of integrated design approaches are often based on level i, ii or iii since the current information sharing between PD and PSD is often managed with the limited accessibility. For instance, information is occasionally shared or exchanged for the specific and critical cases such as quality issue, design improvement or cost reduction activity where the only small amount of information related specific issue is shared between these two design processes. Ideally, in the P&PS co-design process, the information sharing tools must be based on level iv capability in order to enable full interaction between design processes.

To support a programme of continuous improvement (for training designers and enhancing the level of information and knowledge interchange within the design), this research defined a set of simple guidelines, in Table 9.1 and 9.2 which are adapted from (Maier *et al.* 2008). These tables aim to provide the ability to assess the existing level of capability by a company's information sharing practice and tool as well as devise a stepwise approach to improve this capability towards level iv required by the P&PS co-design process based on Awareness strategy.

*Table 9.1 - Check sheet for evaluating performance of information sharing between product-production system design: Product design sheet*

| **An evaluation of information sharing practice<br>(by product designer)** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **No.** | **Aspect related information sharing** | **Factor** | **Definition** | **Level of information sharing practice** | | | | **Current practice** |
| | | | | **Level - i** | **Level - ii** | **Level - iii** | **Level - iv** | |
| 1 | Understanding of Production system information | Representation | Degree of understanding and adequacy of the different types of representations of a production system (e.g., production processes). | Production department has its own way of representing information and it is unclear to us | Production department has its own way of representing information and it is somewhat clear to us | Production department has its own way of representing information and it is mostly clear to us | Production department has its own way of representing information and it is always clear to us | |
| 2 | | Notation | Degree of understandingn of ''for example'' drawing conventions. | Production department uses its own notation and it is unclear to us | Production department uses its own notation and it is somewhat clear to us | Production department uses its own notation and it is mostly clear to us | Production department uses its own notation and it is always clear to us. | |
| 3 | | Terminology | Degree of understanding of specific technical terms used. | Production department uses its own terminology and it is unclear to us | Production department use its own terminology and it is somewhat clear to us | Production department uses its own terminology and it is mostly clear to us | Production design department uses its own terminology and it is always clear to us. Or, Production design department shared the same terminologies | |
| 4 | Availability of production system information | Availability of information about our company's production | How often information about the own company's production is distributed to designer. | Not necessary | If I ask for it | it is regularly distributed to me | Regularly and there is continuous effort to adjust the distribution process according to needs | |
| 5 | | Availability of information about production specifications | How often information about production specifications is distributed todesigner. | Not necessary | If I ask for it | it is regularly distributed to me | Regularly and there is continuous effort to adjust the distribution process according to needs | |
| 6 | | Availability of information about collaboration procedures | How often information about procedures is distributed to designer. | Not necessary | If I ask for it | it is regularly distributed to me | Regularly and there is continuous effort to adjust the distribution process according to needs | |
| 7 | | Information sharing tools | Level of information accessibility | Other users can only access information when owner provides the accessiblity | Multiple users can access information which can be modified by an owner only. | Multiple users can access and sequential modify information which is however requested final approval from an owner. | Multiple users can access and modify information in parallel; nonetheless, the modification requires the approval by all related members. | |

*Table 9.2 - Check sheet for evaluating performance of information sharing between product-production system designs: Production system design sheet*

| **An evaluation of information sharing practice (by production system designer)** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **No.** | **Aspect related information sharing** | **Factor** | **Definition** | **Level of information sharing practice** | | | | **Current practice** |
| | | | | **Level - i** | **Level - ii** | **Level - iii** | **Level - iv** | |
| 1 | Understanding of Product information | Representation | Degree of understanding and adequacy of the different types of representations of aproduct (e.g., bill of materials, drawings). | Product design department has its own way of representing information and it is unclear to us | Product design department has its own way of representing information and it is somewhat clear to us | Product design department has its own way of representing information and it is mostly clear to us | Product design department has its own way of representing information and it is always clear to us | |
| 2 | | Notation | Degree of understanding of ‘‘for example’’ drawing conventions. | Product design department uses its own notation and it is unclear to us | Product design department uses its own notation and it is somewhat clear to us | Product design department uses its own notation and it is mostly clear to us | Product design department uses its own notation and it is always clear to us. | |
| 3 | | Terminology | Degree of understanding of specific technical terms used. | Product design department uses its own terminology and it is unclear to us | Product design department use its own terminology and it is somewhat clear to us | Product design department uses its own terminology and it is mostly clear to us | Product design department uses its own terminology and it is always clear to us. Or, Product design department shared the same terminologies | |
| 4 | Availability of product design information | Availability of information about our company's products | How often information about the own company's product is distributed to designer. | Not necessary | If I ask for it | it is regularly distributed to me | Regularly and there is continuous effort to adjust the distribution process according to needs | |
| 5 | | Availability of information about product design specifications | How often information about product design specifications is distributed todesigner. | Not necessary | If I ask for it | it is regularly distributed to me | Regularly and there is continuous effort to adjust the distribution process according to needs | |
| 6 | | Availability of information about collaboration procedures | How often information about collaboration procedures is distributed to designer. | Not necessary | If I ask for it | it is regularly distributed to me | Regularly and there is continuous effort to adjust the distribution process according to needs | |
| 7 | | Information sharing tools | Level of information accessibility | Other users can only access information when owner provides the accessiblity | Multiple users can access information which can be modified by an owner only. | Multiple users can access and sequential modify information which is however requested final approval from an owner. | Multiple users can access and modify information in parallel; nonetheless, the modification requires the approval by all related members. | |

## 9.4 STRATEGY II: ASSOCIATION THROUGH A CLOSER COLLABORATION BETWEEN P&PS DESIGN

The second strategy for implementing of co-design processes is recommended for companies where their interrelation between product and production system designs are relatively complicated due to a number of interdependencies between many co-design decisions. In this strategy, however, the close collaboration and/or combination of design processes is only limited to a subset of overall design processes due to a range of conditions such as design conflicts with legacy systems/procedures, costly operational changes, or in cases where the potential benefits of a co-design approach are limited to a subset of design decisions. For example, in high precision manufacturing applications (e.g. a jet-engine), the product and production system designs are very restricted, and any design changes are constrained tightly by specific product characteristics such as the need for zero defect due to high risk associated to product failure. In such cases, only a subset of decisions could be supported by a co-design approach through the adoption of '**Association**' strategy for implementation of the P&PS co-design process.

To realise this strategy, **closer collaboration** between P&PS designers must be established in order to facilitate a direct involvement of key designers with various backgrounds within a single process for co-designing resource-efficient P&PS. For example, in the case of a footwear company, the shoe design information is only utilised at the end of product design for developing production system layout (i.e. defining a production process chain). In this case, a collaboration between PD and PSD designers is occasionally organised only when redesign issue is raised. Therefore, to achieve the benefit of P&PS co-design, the 'closer design collaboration' needs to be arranged, as shown in the To-be diagram (see Figure 9.3). This is when both P&PS designers collectively make ecological decisions related to a selection of shoe material and geometry as well as pre-development of fabrication and assembly process during conceptual design, as identified in step 2.1 of Co-specify phase (see Table 8.8 and 8.9).

In this context, the Association strategy might be considered as an expansion of 'DfM' in which a more comprehensive range of production system information and knowledge are made available during product design. The main objective in a DfM approach is to ensure the availability of manufacturing facilities to produce a product, whereas in P&PS co-design process the need for a bi-directional flow of information and knowledge is extended (i.e. from PD to PSD) to unlock the infinite capability of design decisions to optimise resource efficiency.

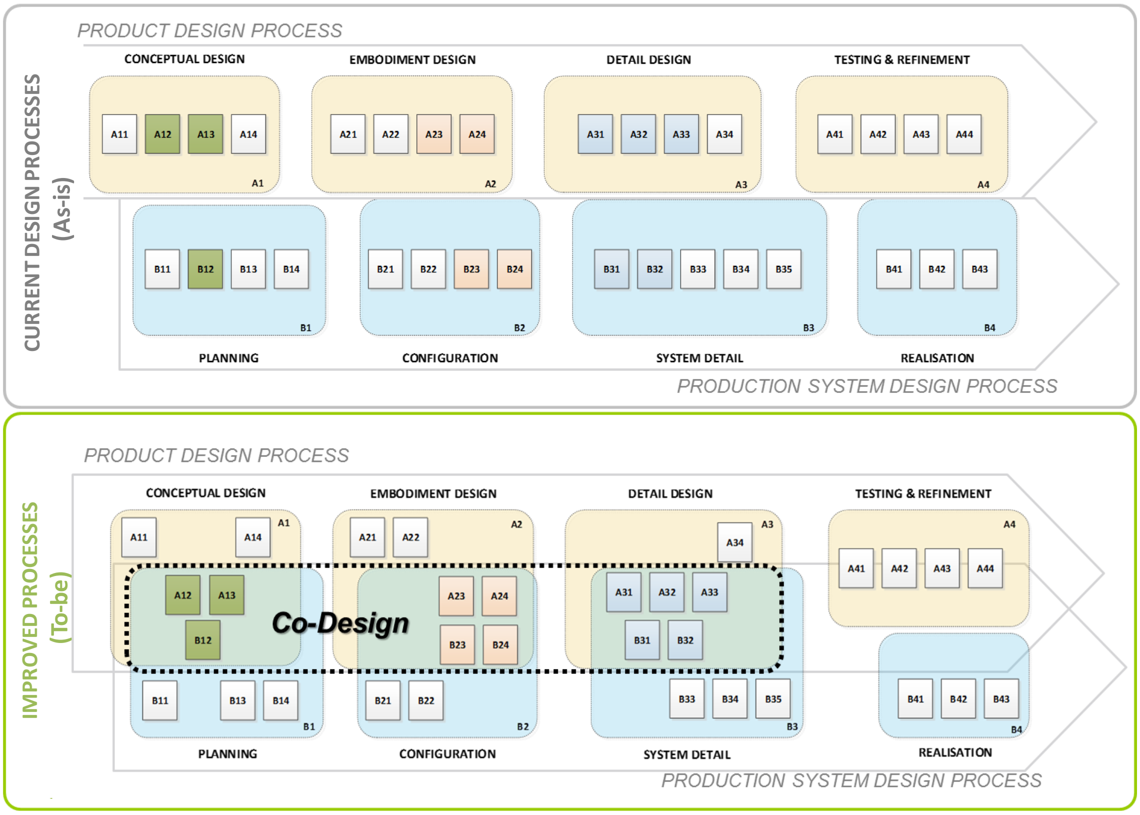


*Figure 9.3 - Co-design by the Association through closer collaboration between P&PS designers*

### *9.4.1 Establishing closer collaboration between P&PS co-design decision-making*

In a similar manner to Awareness strategy, the results from steps 2.1 - 2.3 in the Co-specify phase are used in Association strategy to identify which sub-set of design processes would benefit from establishing closer collaboration between designers. The difference in this second strategy is that the co-design interrelation assessment sheets (see Figure 8.13) that are generated in step 2.2 of co-specify phase highlight a higher degree of interdependencies between product and production system design decisions. For example, in Figure 9.3, three groups of co-design considerations are identified during Co-specify phase which needs to be collaboratively decided by P&PS designers during conceptual product design, embodiment design and detail design stage, as depicted in a 'To-be' information flow. To achieve this, the relevant production system designers involved in these processes are assigned specific additional duties to participate in the product design process. This strategy could not only involve further training for designers (similar to Awareness strategy) but also a reorganisation of the two design teams into a single entity whose member's role, and responsibilities have been redefined to ensure closer collaboration and to operate as one team. In a simple application, this could be based on repositions of designers into the same design office (physical co-design collaboration) or in the case of more complex applications, a redefinition of the workflow model (virtual co-design collaboration), enforcing dependency of design decision makings.

In order to realise this strategy, the relationship between members of such a newly formed P&PS design team should be defined to ensure the efficiency of the collaborative design. In this context, the current design relationship can be basically classified into four different levels, namely interaction, coordination, cooperation, and collaboration, as defined by Lu *et al.* (2007) :

i. Interaction – different teams separately manage task with very limited communication
ii. Coordination – different teams unidirectionally manage tasks with different objectives
iii. Cooperation – different teams bidirectionally manage tasks with the shared resource, procedure and benefits
iv. Collaboration – a combination of teams, jointly manages tasks with the shared resource, procedure, benefits and common goal

While the relationship in the current integrated design approaches is often based on levels i, ii or iii, ideally in the P&PS co-design process, this must be based on level iv (collaboration). To support a programme of continuous improvement in training designers and enhancing the level of interaction, a collaboration performance checklist is readapted from Maier *et al.* (2008) and summarised in Table 9.3 and 9.4. This checklist is based on an 'interaction communication grid' method which was originally applied to assess communication effectiveness in a collaborative product development process (Maier *et al.* 2008). These tables aim to provide the ability to assess the existing level of collaboration and provide an approach to improve this capability towards level iv, required by the P&PS co-design process based on Association strategy. This can be achieved through the 'collaboration improvement plan' outlined in Table 9.5, in which communication and collaboration procedures are initially assessed, and a transformation path from no communication or reactive communication procedures (in level i & ii) towards continuous proactive communication procedures (in level iv) is implemented. Similarly, in this plan, a stepwise approach from no collaboration or unfollowed collaboration procedures (in level i & ii) towards a continuous improvement collaboration procedure is employed.

Table 9.3 - Check sheet for evaluating performance of collaboration between product-production system design: Product design sheet

| Collaboration performance evaluation<br>(by product designer) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **No.** | **Aspect related collaboration** | **Factor** | **Definition** | **Level of collaboration maturity** | | | | **Current practice** |
| | | | | **Interaction [Level - i]** | **Coordination [Level - ii]** | **Cooperation [Level - iii]** | **Collaboration [Level - iv]** | |
| 1 | Interaction with production system design in practice | Do you know which information production designer needs? | Degree of the awareness of production designers needs and preferences. | No | Sometimes, we learn from mistakes | Mostly since it is documented and communicated which information is needed | It is entirely clear to us what information we need and the information transmission process is continuously optimised | |
| 2 | | Activity at interface with production designer | Degree of activity with regard to the interface with production designer | They tend to forget us | Their communication is reactive | Their communication is proactive | Our communication with each other is continuously proactive depending on need | |
| 3 | | Handling of technical conflicts | How often technical conflicts are addressed and resolved. | Conflicts are always addressed | Conflicts are sometimes addressed if it can't be avoided anymore | Conflicts are mostly addressed and solutions are planned | Conflicts are always addressed. There is continuous effort to optimise handling of conflicts, to find solutions and to implement them by using insights from previous cases | |
| 4 | Organisation element influencing collaboration performance | Understanding of roles and responsibilities | Knowledge about the roles and responsibilities of oneself and others and the use of it while communicating. | Not clearly defined | Mine and others' are somewhat clear to me | I am fully aware of mine and somewhat aware of others' | I know mine and others' for every task and use it consciously while communicating | |
| 5 | | Goals and objectives of collaboration with production system design | Knowledge and pursuit of common goals and objectives. | Not known. Not thinking about it | Known but everyone follows just his or her own goals | Known and sometimes consideration of the way common goals can be reached through working together | Entirely clear and identification with it which is expressed in communication and continuous effort to assess and adjust goals and objectives and the way to reach them | |

*Table 9.4 - Check sheet for evaluating performance of collaboration between product-production system designs: Production system design sheet*

| Collaboration performance evaluation<br>(by production system designer) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **No.** | **Aspect related collaboration** | **Factor** | **Definition** | **Level of collaboration maturity** | | | | **Current practice** |
| | | | | **Interaction [Level - i]** | **Coordination [Level - ii]** | **Cooperation [Level - iii]** | **Collaboration [Level - iv]** | |
| 1 | Interaction with product design in practice | Do you know which information product designer needs? | Degree of the awareness of product designer needs and preferences. | No | Sometimes, we learn from mistakes | Mostly since it is documented and communicated which information is needed | It is entirely clear to us what information we need and the information transmission process is continuously optimised | |
| 2 | | Activity at interface with product designer | Degree of activity with regard to the interface with product designer | They tend to forget us | Their communication is reactive | Their communication is proactive | Our communication with each other is continuously proactive depending on need | |
| 3 | | Handling of technical conflicts | How often technical conflicts are addressed and resolved. | Conflicts are always addressed | Conflicts are sometimes addressed if it can't be avoided anymore | Conflicts are mostly addressed and solutions are planned | Conflicts are always addressed. There is continuous effort to optimise handling of conflicts, to find solutions and to implement them by using insights from previous cases | |
| 4 | Organisation element influencing collaboration performance | Understanding of roles and responsibilities | Knowledge about the roles and responsibilities of oneself and others and the use of it while communicating. | Not clearly defined | Mine and others' are somewhat clear to me | l am fully aware of mine and somewhat aware of others' | I know mine and others' for every task and use it consciously while communicating | |
| 5 | | Goals and objectives of collaboration with product design | Knowledge and pursuit of common goals and objectives. | Not known. Not thinking about it | Known but everyone follows just his or her own goals | Known and sometimes consideration of the way common goals can be reached through working together | Entirely clear and identification with it which is expressed in communication and continuous effort to assess and adjust goals and objectives and the way to reach them | |

*Table 9.5 - Collaboration improvement plan during the Co-create phase*

Collaboration Improvement for Co-design implementation ↑

| Level | Communication | Collaboration procedure |
|---|---|---|
| **Collaboration [iv]** | Continuous proactive | Continuous improving |
| **Cooperation [iii]** | Proactive | Follow |
| **Coordination [ii]** | Reactive | Unfollow |
| **Interaction [i]** | No communication | No procedure |

## 9.5 STRATEGY III: ADAPTATION INTO A COMBINED CO-DESIGN PROCESS FOR PRODUCT AND PRODUCTION SYSTEM

This strategy is recommended to support companies where the complexity of interrelation between P&PS design is critically high because of the number of interdependencies between many co-design decisions within their design processes. In such cases, to gain the maximum potential benefits and to respond to the high complexity of co-design decisions, it is recommended that the existing independent processes should be completely transformed into P&PS co-design process through utilisation of '**Adaptation**' strategy.

This Adaptation strategy can be considered as a revolutionary approach to changing the design process, aiming to **combine two independent processes into a single one for a concurrent approach to co-designing P&PS**. This single process can be constructed by decomposing the independent product and production system design processes into a number of design activities (and/or decisions), and restructuring and reorganising these into a combined process, as illustrated in a 'To-be' diagram in Figure 9.4. This new P&PS co-design process is operated by the reskilled designers who previously were product or production system designers. In contrast with the Awareness and Association strategies, the designers in Adoption approach need to have the complete knowledge of P&PS design instead of a part of PD and/or PSD related only to a subset of targeted decisions (See Section 9.3). Therefore, with this new role and responsibilities for P&PS designers, the structure of the design team is completely changed to manage the design process within one organisational unit.

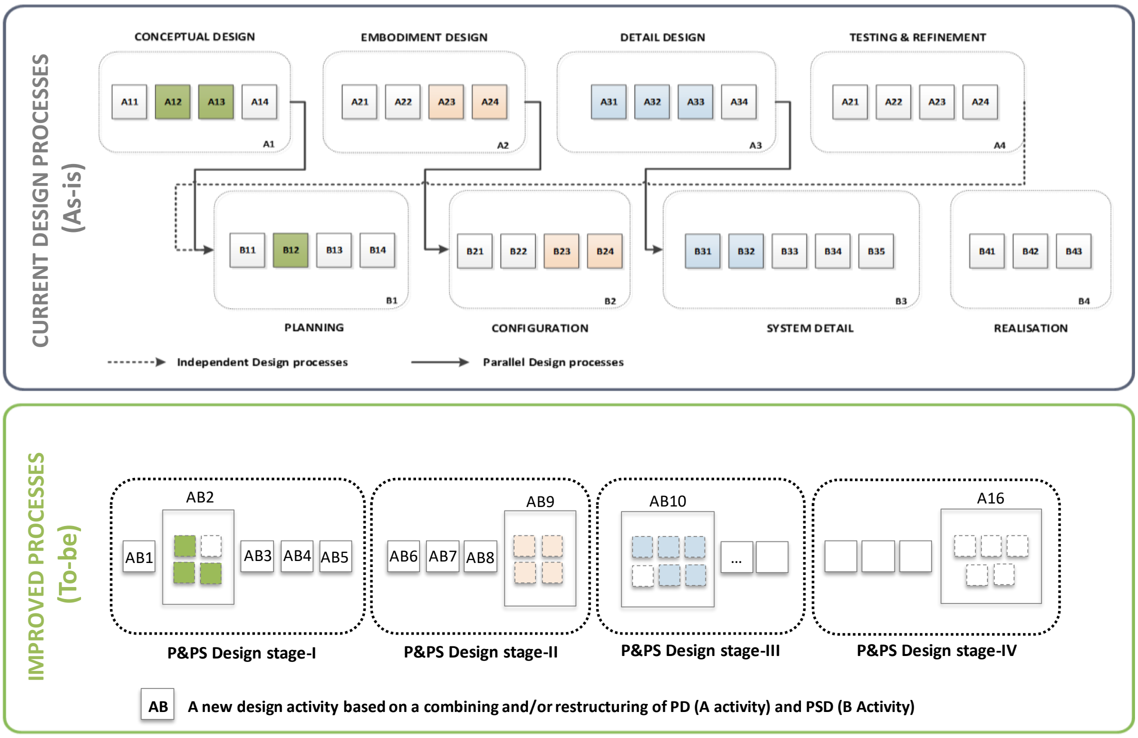


*Figure 9.4 - Co-design by the Adaptation into a combined co-design process*

The Adaption strategy therefore offers a step-by-step approach for identifying the relationship pattern between various design activities and re-sequencing these into a P&PS co-design process, as explained in the following subsection.

### 9.5.1 Identifying the relationship pattern and re-sequencing the design activities into the P&PS co-design process

The Adaptation strategy utilises the Design Structure Matrix (DSM) method (Danilovic and Browning 2007) to restructure the various design activities identified as part of step 2.3 in Co-specify phase (See Table 8.9 and 8.10) into a new single co-design process. The DSM has been widely applied to support the improvement of design process flow through process decomposition and sequencing, outlining input/output/feedback and process iteration, and highlighting interdependency between design activities (Eppinger and Browning, 2012). In this context, to construct a new P&PS co-design process, the following two steps must be undertaken.

In step 1 the relationship pattern of design activities must be identified using the design process model outlined in Section 8.3.2. This is achieved by listing all P&PS design activities across the rows (on the left-hand side of the DSM table) and columns (on the top of the DSM table), and by inserting ‘x’ in cross-sections in which an information flow is required between the two design activities under considerations (see Table 9.6). For example in Figure 9.5, activity B requires input information from the output of activities A (i.e. they are dependent), and activities C & D do not need information exchange (i.e. they are independent). Activities E and F need information from each other (i.e. they are interdependent, and finally both activities G & H required to input information from activity F (i.e. they are contingent). In this context, the relationship pattern of A to H design activities can be classified into these four main types of Dependent (sequential activities), Independent (parallel activities), Interdependent (coupled activities) and Contingent (conditional activities).

In the second step, all but the independent activities are re-sequenced to improve the performance of design process by minimising 'the size of information feedback loop' (i.e. provide information in a timely fashion to support a key design decision), as proposed by DSM methods. For example, in Table 9.6, the interdependent activities A31 and A32 have an efficient feedback loop (i.e. Feedback loop 1) since activity A32 can immediately start and can directly feed information back to A31 in order to complete both activities. In contrast, activity A12, B12 and several other activities between them have an inefficient feedback look (i.e. feedback loop 2) as all activities cannot be achieved until the A12 and B12 are undertaken and finalised. Hence, this large feedback loop must be re-sequenced using the following guidelines (Eppinger and Browning, 2012):

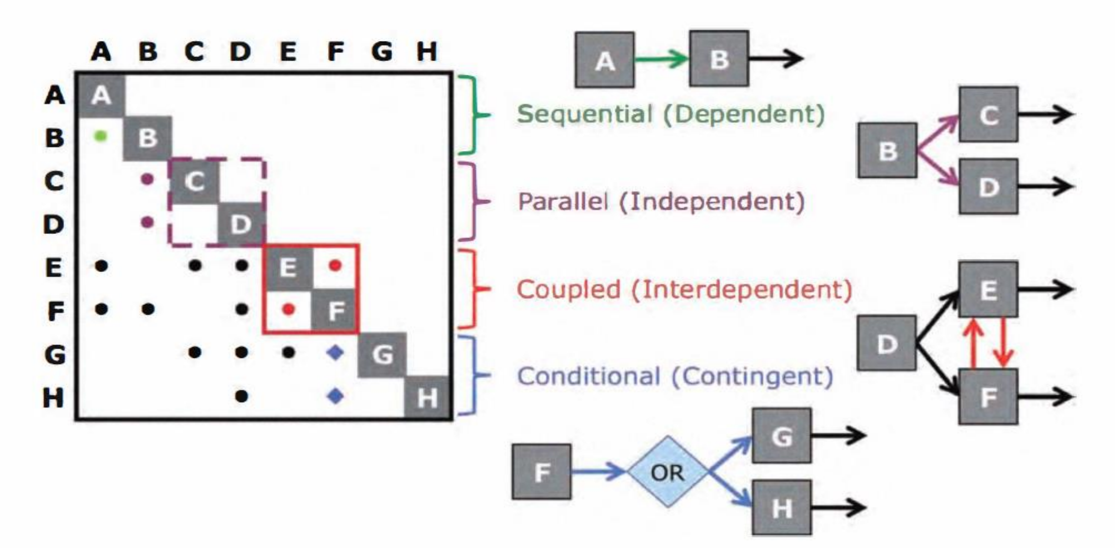
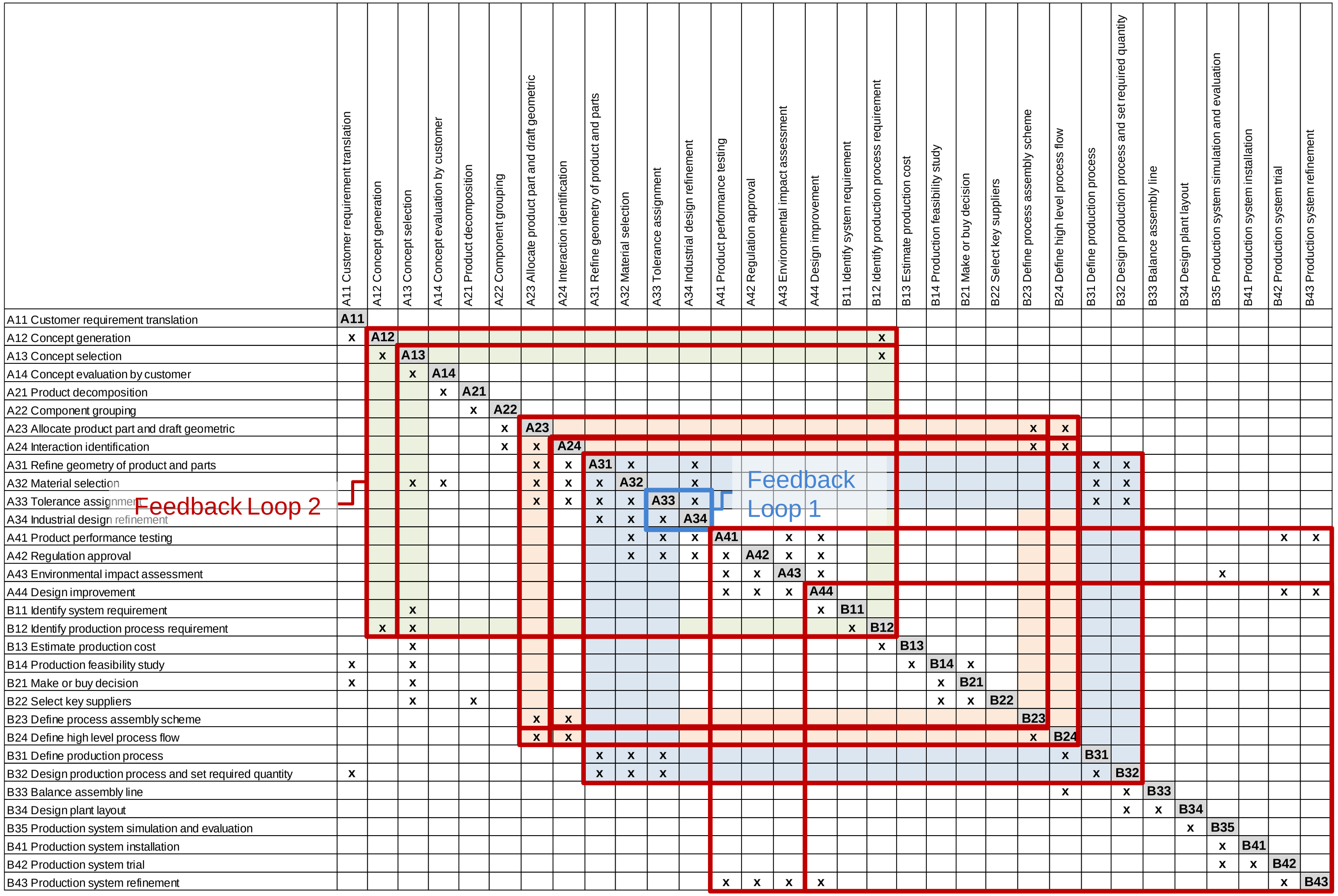


*Figure 9.5 - Four main types of relationship between activities in process flow* (Eppinger and Browning 2012)

Table 9.6 - Activities in design processes for footwear and its production system before re-sequencing via design structure matrix



| | A11 Customer requirement translation | A12 Concept generation | A13 Concept selection | A14 Concept evaluation by customer | A21 Product decomposition | A22 Component grouping | A23 Allocate product part and draft geometric | A24 Interaction identification | A31 Refine geometry of product and parts | A32 Material selection | A33 Tolerance assignment | A34 Industrial design refinement | A41 Product performance testing | A42 Regulation approval | A43 Environmental impact assessment | A44 Design improvement | B11 Identify system requirement | B12 Identify production process requirement | B13 Estimate production cost | B14 Production feasibility study | B21 Make or buy decision | B22 Select key suppliers | B23 Define process assembly scheme | B24 Define high level process flow | B31 Define production process | B32 Design production process and set required quantity | B33 Balance assembly line | B34 Design plant layout | B35 Production system simulation and evaluation | B41 Production system installation | B42 Production system trial | B43 Production system refinement |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| A11 Customer requirement translation | **A11** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| A12 Concept generation | x | **A12** | | | | | | | | | | | | | | | | x | | | | | | | | | | | | | | |
| A13 Concept selection | | x | **A13** | | | | | | | | | | | | | | | x | | | | | | | | | | | | | | |
| A14 Concept evaluation by customer | | | x | **A14** | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| A21 Product decomposition | | | | x | **A21** | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| A22 Component grouping | | | | | x | **A22** | | | | | | | | | | | | | | | | | | | | | | | | | | |
| A23 Allocate product part and draft geometric | | | | | | x | **A23** | | | | | | | | | | | | | | | | x | x | | | | | | | | |
| A24 Interaction identification | | | | | | x | x | **A24** | | | | | | | | | | | | | | | x | x | | | | | | | | |
| A31 Refine geometry of product and parts | | | | | | | x | x | **A31** | x | | x | | | | | | | | | | | | | x | x | | | | | | |
| A32 Material selection | | | x | x | | | x | x | x | **A32** | | x | | | | | | | | | | | | | x | x | | | | | | |
| A33 Tolerance assignment | | | | | | | x | x | x | x | **A33** | x | | | | | | | | | | | | | x | x | | | | | | |
| A34 Industrial design refinement | | | | | | | | | x | x | x | **A34** | | | | | | | | | | | | | | | | | | | | |
| A41 Product performance testing | | | | | | | | | | x | x | x | **A41** | | x | x | | | | | | | | | | | | | | | x | x |
| A42 Regulation approval | | | | | | | | | | x | x | x | x | **A42** | x | x | | | | | | | | | | | | | | | | |
| A43 Environmental impact assessment | | | | | | | | | | | | | x | x | **A43** | x | | | | | | | | | | | | | x | | | |
| A44 Design improvement | | | | | | | | | | | | | x | x | x | **A44** | | | | | | | | | | | | | | | x | x |
| B11 Identify system requirement | | | x | | | | | | | | | | | | | x | **B11** | | | | | | | | | | | | | | | |
| B12 Identify production process requirement | | x | x | | | | | | | | | | | | | | x | **B12** | | | | | | | | | | | | | | |
| B13 Estimate production cost | | | x | | | | | | | | | | | | | | | x | **B13** | | | | | | | | | | | | | |
| B14 Production feasibility study | x | | x | | | | | | | | | | | | | | | | x | **B14** | x | | | | | | | | | | | |
| B21 Make or buy decision | x | | x | | | | | | | | | | | | | | | | | x | **B21** | | | | | | | | | | | |
| B22 Select key suppliers | | | x | | x | | | | | | | | | | | | | | | x | x | **B22** | | | | | | | | | | |
| B23 Define process assembly scheme | | | | | | | x | x | | | | | | | | | | | | | | | **B23** | | | | | | | | | |
| B24 Define high level process flow | | | | | | | x | x | | | | | | | | | | | | | | | x | **B24** | | | | | | | | |
| B31 Define production process | | | | | | | | | x | x | x | | | | | | | | | | | | | x | **B31** | | | | | | | |
| B32 Design production process and set required quantity | x | | | | | | | | x | x | x | | | | | | | | | | | | | | x | **B32** | | | | | | |
| B33 Balance assembly line | | | | | | | | | | | | | | | | | | | | | | | | x | | x | **B33** | | | | | |
| B34 Design plant layout | | | | | | | | | | | | | | | | | | | | | | | | | | x | x | **B34** | | | | |
| B35 Production system simulation and evaluation | | | | | | | | | | | | | | | | | | | | | | | | | | | | x | **B35** | | | |
| B41 Production system installation | | | | | | | | | | | | | | | | | | | | | | | | | | | | | x | **B41** | | |
| B42 Production system trial | | | | | | | | | | | | | | | | | | | | | | | | | | | | | x | x | **B42** | |
| B43 Production system refinement | | | | | | | | | | | | | x | x | x | x | | | | | | | | | | | | | | | x | **B43** |

i. Identify feedback loops for all interdependent activities (see 'red' feedback loops in Tables 9.6)
ii. Group together all activities within a loop as a single activity (For instance, group 1: A12, A13 and B12; Group 2: A23, A24, B23 and B24 in Table 9.6)
iii. Sequence the dependent, independent and contingent activities based on all empty rows (which require no further information) to be performed first and all empty columns (which provide no information to other activities) to be performed last. Once an activity is sequenced, remove it from further consideration and repeat this procedure until no empty rows or columns remains.
iv. Consider the identified groups of interdependent activities (in step ii) as a single activity and sequence these groups following the guidelines in step iii.
v. Repeat steps iii. and iv. until there is a minimum number of information required for previous activities, as shown in Table 9.7.

The application of the abovementioned procedure for resequencing for the design activities within a footwear manufacturer, presented in Table 9.6 and 9.7, has resulted in four groups of co-design activities, as shown in Table 9.8 and listed below:

Group 1: Customer requirement translation, P&PS requirement identification, concept generation, concept selection, production cost estimation, feasibility study and evaluated concept selection.
Group 2: Product decomposition, component grouping, selecting the main suppliers, allocating product part and draft geometry, identifying part interaction and defining the assembly scheme, as well as defining high-level process flow
Group 3: Refinement of material, P&PS geometry and P&PS tolerance, design production processes, balance assembly line and refine plant layout
Group 4: Simulate, test, evaluate, refine and revise the P&PS as well as regulatory approval.

Such resequencing of Dependent, Independent, Interdependent and Contingent (conditional activities) is reported to minimise design process duration and cost (Eppinger and Browning, 2012).

Table 9.7 - Activities in design processes for footwear and its production system after re-sequencing via design structure matrix

| | A11 Customer requirement translation | A12 Concept generation | A13 Concept selection | B11 Identify system requirement | B12 Identify production process requirement | B13 Estimate production cost | B14 Production feasibility study | B21 Make or buy decision | A14 Concept evaluation by customer | A21 Product decomposition | A22 Component grouping | B22 Select key suppliers | A23 Allocate product part and draft geometric | A24 Interaction identification | B23 Define process assembly scheme | B24 Define high level process flow | A31 Refine geometry of product and parts | A32 Material selection | A33 Tolerance assignment | A34 Industrial design refinement | B31 Define production process | B32 Design production process and set required quantity | B33 Balance assembly line | B34 Design plant layout | B35 Production system simulation and evaluation | B41 Production system installation | B42 Production system trial | A41 Product performance testing | A42 Regulation approval | B43 Production system refinement | A43 Environmental impact assessment | A44 Design improvement |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| A11 Customer requirement translation | A11 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| A12 Concept generation | x | A12 | | | x | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| A13 Concept selection | | x | A13 | | x | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| B11 Identify system requirement | | | x | B11 | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| B12 Identify production process requirement | | x | x | x | B12 | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| B13 Estimate production cost | | | x | | x | B13 | | | | | | | | | | | | | | | | | | | | | | | | | | |
| B14 Production feasibility study | x | | x | | | x | B14 | | | | | | | | | | | | | | | | | | | | | | | | | |
| B21 Make or buy decision | x | | x | | | | x | B21 | | | | | | | | | | | | | | | | | | | | | | | | |
| A14 Concept evaluation by customer | | | x | | | | | | A14 | | | | | | | | | | | | | | | | | | | | | | | |
| A21 Product decomposition | | | | | | | | | x | A21 | | | | | | | | | | | | | | | | | | | | | | |
| A22 Component grouping | | | | | | | | | | x | A22 | | | | | | | | | | | | | | | | | | | | | |
| B22 Select key suppliers | | | x | | | | x | x | | | x | B22 | | | | | | | | | | | | | | | | | | | | |
| A23 Allocate product part and draft geometric | | | | | | | | | | | x | | A23 | | x | x | | | | | | | | | | | | | | | | |
| A24 Interaction identification | | | | | | | | | | | x | | x | A24 | x | x | | | | | | | | | | | | | | | | |
| B23 Define process assembly scheme | | | | x | x | | | | | | | | x | x | B23 | | | | | | | | | | | | | | | | | |
| B24 Define high level process flow | | | | | | | | | | | | | x | x | x | B24 | | | | | | | | | | | | | | | | |
| A31 Refine geometry of product and parts | | | | | | | | | | | | | x | x | | | A31 | x | | x | x | x | | | | | | | | | | |
| A32 Material selection | | | x | | | | | | x | | | | x | x | | | x | A32 | | x | x | x | | | | | | | | | | |
| A33 Tolerance assignment | | | | | | | | | | | | | x | x | | | x | x | A33 | x | x | x | | | | | | | | | | |
| A34 Industrial design refinement | | | | | | | | | | | | | | | | | x | x | x | A34 | | | | | | | | | | | | |
| B31 Define production process | | | | | x | | | | | | | | x | x | | x | x | x | x | | B31 | | | | | | | | | | | |
| B32 Design production process and set required quantity | x | | | | x | | | | | | | | | | | | x | x | x | | x | B32 | | | | | | | | | | |
| B33 Balance assembly line | | | | x | | | | | | | | | | | | x | | | | | | x | B33 | | | | | | | | | |
| B34 Design plant layout | | | | x | | | | | | | | | | | | | | | | | | x | x | B34 | | | | | | | | |
| B35 Production system simulation and evaluation | | | | | | | | | | | | | | | | | | | | | | | | x | B35 | | | | | | | |
| B41 Production system installation | | | | | | | | | | | | | | | | | | | | | | | | | x | B41 | | | | | | |
| B42 Production system trial | | | | | | | | | | | | | | | | | | | | | | | | | x | x | B42 | | | | | |
| A41 Product performance testing | | | | | | | | | | | | | | | | | | x | x | x | | | | | | | x | A41 | x | x | x | x |
| A42 Regulation approval | | | | | | | | | | | | | | | | | x | x | x | x | | | | | | | | x | A42 | | x | x |
| B43 Production system refinement | | | | | | | | | | | | | | | | | | | | | | | | | | | x | x | x | B43 | x | x |
| A43 Environmental impact assessment | | | | | | | | | | | | | | | | | | | | | | | | | x | | | x | x | | A43 | x |
| A44 Design improvement | | | | | | | | | | | | | | | | | | | | | | | | | | | x | x | x | x | x | A44 |

*Table 9.8 - the possible form of co-design stage based on the information flow and original practice between two design processes*

| | A11 Customer requirement translation | A12 Concept generation | A13 Concept selection | B11 Identify system requirement | B12 Identify production process requirement | B13 Estimate production cost | B14 Production feasibility study | B21 Make or buy decision | A14 Concept evaluation by customer | A21 Product decomposition | A22 Component grouping | B22 Select key suppliers | A23 Allocate product part and draft geometric | A24 Interaction identification | B23 Define process assembly scheme | B24 Define high level process flow | A31 Refine geometry of product and parts | A32 Material selection | A33 Tolerance assignment | A34 Industrial design refinement | B31 Define production process | B32 Design production process and set required quantity | B33 Balance assembly line | B34 Design plant layout | B35 Production system simulation and evaluation | B41 Production system installation | B42 Production system trial | A41 Product performance testing | A42 Regulation approval | B43 Production system refinement | A43 Environmental impact assessment | A44 Design improvement |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| A11 Customer requirement translation | A11 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| A12 Concept generation | x | A12 | | | x | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| A13 Concept selection | | x | A13 | | x | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| B11 Identify system requirement | | | x | B11 | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| B12 Identify production process requirement | | x | x | x | B12 | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| B13 Estimate production cost | | | x | | x | B13 | | | | | | | | | | | | | | | | | | | | | | | | | | |
| B14 Production feasibility study | x | | x | | | x | B14 | | | | | | | | | | | | | | | | | | | | | | | | | |
| B21 Make or buy decision | x | | x | | | | x | B21 | | | | | | | | | | | | | | | | | | | | | | | | |
| A14 Concept evaluation by customer | | | x | | | | | | A14 | | | | | | | | | | | | | | | | | | | | | | | |
| A21 Product decomposition | | | | | | | | | x | A21 | | | | | | | | | | | | | | | | | | | | | | |
| A22 Component grouping | | | | | | | | | | x | A22 | | | | | | | | | | | | | | | | | | | | | |
| B22 Select key suppliers | | | x | | | | x | x | | | x | B22 | | | | | | | | | | | | | | | | | | | | |
| A23 Allocate product part and draft geometric | | | | | | | | | | | x | | A23 | | x | x | | | | | | | | | | | | | | | | |
| A24 Interaction identification | | | | | | | | | | | x | | x | A24 | x | x | | | | | | | | | | | | | | | | |
| B23 Define process assembly scheme | | | | x | x | | | | | | | | x | x | B23 | | | | | | | | | | | | | | | | | |
| B24 Define high level process flow | | | | | | | | | | | | | x | x | x | B24 | | | | | | | | | | | | | | | | |
| A31 Refine geometry of product and parts | | | | | | | | | | | | | x | x | | | A31 | x | | x | x | x | | | | | | | | | | |
| A32 Material selection | | | x | | | | | | x | | | | x | x | | | x | A32 | | x | x | x | | | | | | | | | | |
| A33 Tolerance assignment | | | | | | | | | | | | | x | x | | | x | x | A33 | x | x | x | | | | | | | | | | |
| A34 Industrial design refinement | | | | | | | | | | | | | | | | | x | x | x | A34 | | | | | | | | | | | | |
| B31 Define production process | | | | | x | | | | | | | | x | x | | x | x | x | x | | B31 | | | | | | | | | | | |
| B32 Design production process and set required quantity | x | | | | x | | | | | | | | | | | | x | x | x | | x | B32 | | | | | | | | | | |
| B33 Balance assembly line | | | | x | | | | | | | | | | | | x | | | | | | x | B33 | | | | | | | | | |
| B34 Design plant layout | | | | x | | | | | | | | | | | | | | | | | | x | x | B34 | | | | | | | | |
| B35 Production system simulation and evaluation | | | | | | | | | | | | | | | | | | | | | | | | x | B35 | | | | | | | |
| B41 Production system installation | | | | | | | | | | | | | | | | | | | | | | | | | x | B41 | | | | | | |
| B42 Production system trial | | | | | | | | | | | | | | | | | | | | | | | | | x | x | B42 | | | | | |
| A41 Product performance testing | | | | | | | | | | | | | | | | | | x | x | x | | | | | | | x | A41 | x | x | x | x |
| A42 Regulation approval | | | | | | | | | | | | | | | | | x | x | x | x | | | | | | | | x | A42 | | x | x |
| B43 Production system refinement | | | | | | | | | | | | | | | | | | | | | | | | | | | x | x | x | B43 | x | x |
| A43 Environmental impact assessment | | | | | | | | | | | | | | | | | | | | | | | | | x | | | x | x | | A43 | x |
| A44 Design improvement | | | | | | | | | | | | | | | | | | | | | | | | | | | x | x | x | x | x | A44 |

## 9.6 CHAPTER SUMMARY

This chapter has outlined the third phase of the P&PS co-design framework, namely the Co-create phase, which is devised based in three strategies provided a step-by-step approach to guide a company in its efforts to improve current design processes through implementation of co-design process. These three strategies, namely Awareness of design knowledge interchange, Association through closer collaboration, and Adaptation into a single co-design process of P&PS can be utilised individually by a company based on the design complexity and interdependencies among their design activities. These could be used as a gradual (continuous improvement) approach for transforming from the existing two independent design processes for product and production systems into one single combine design process.

Within the final stage of the framework, a computer-aided software tool has been developed to support the implementation of the various tasks included in the initial three phases of P&PS co-design framework. This fourth Co-implement phase of P&PS co-design framework is discussed in detail in the next chapter (Chapter 10).

# CHAPTER 10 IMPLEMENTING THE NOVEL FRAMEWORK FOR CO-DESIGNING PROCESSES OF PRODUCTS AND PRODUCTION SYSTEMS

## 10.1 INTRODUCTION

This chapter describes the fourth and the final phase of P&PS Co-design framework, namely the Co-implement phase, which aims to support the application of this framework through a specially designed software toolkit, generated by the research reported in this thesis. In addition, the use of existing commercial design software tools to further support the various implementation aspects of the P&PS framework is also discussed in this chapter.

## 10.2 PHASE 4: CO-IMPLEMENT PHASE

The Co-implement phase supports the implementation of the various steps defined as part of phases 1-3 of the P&PS Co-design framework, as depicted in Figure 10.1. The implementation of these steps requires significant information gathering, recording and processing. Thus, this research has generated a specially designed software toolkit, referred to as of Product and Production system Co-design (PPC) software tool. In brief, this toolkit consists of a number of modules, developed using Microsoft Excel and Visual Basic Programming Language for supporting data collection, automatic data analysis, and visualisation and presentation of results in a user-friendly manner to relevant designers. An overview of the system structure for the PPC comprising of inputs, outputs, user interface, database and functional modules, is illustrated in Figure 10.2. Furthermore, the PPC can be used in conjunction with several existing commercial tools and emerging tools introduced by relevant research publications. These consist of the support for application of the Co-initiate phase through utilisation of subSTance flow ANalysis (STAN2.6) software tool (TU Wien Institute 2012) for resource consumption assessment, the realisation of the Co-specify phase through Microsoft VISIO for modelling design process, and finally for support of Co-create phase through Design Structure Metrix V1.6 software tool (Projectdsm 2016) for resequencing the co-design activities.

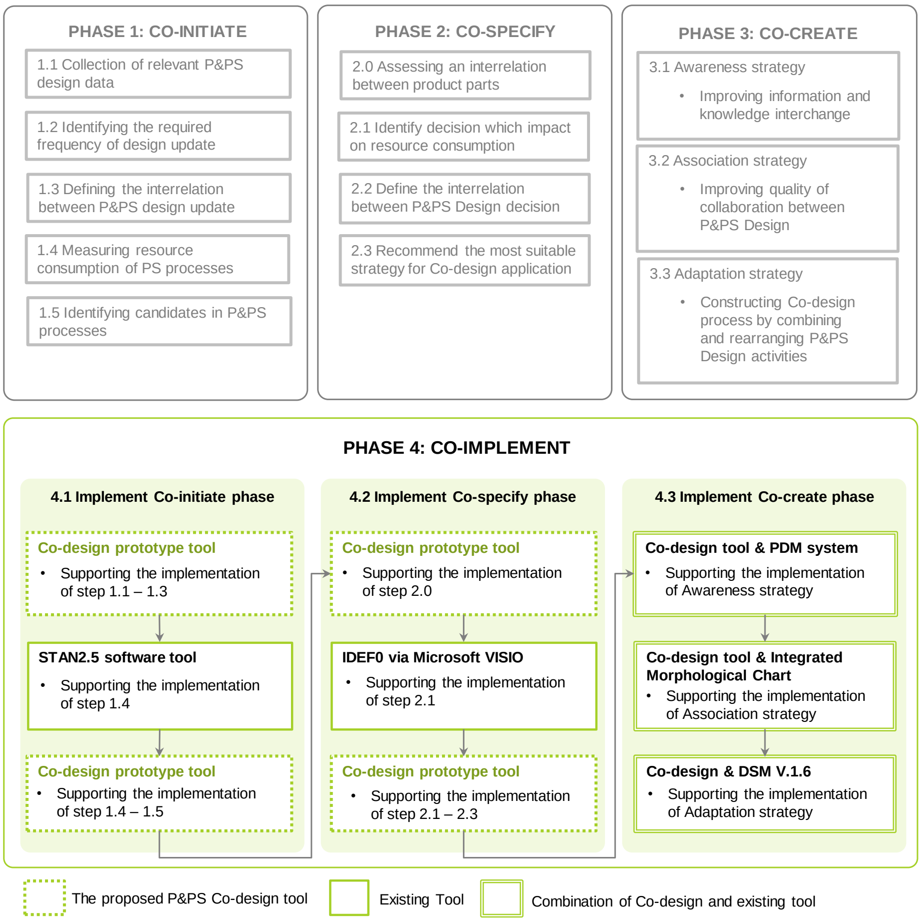


*Figure 10.1 - An overview of the applicable toolkit for the P&PS Co-design framework application*

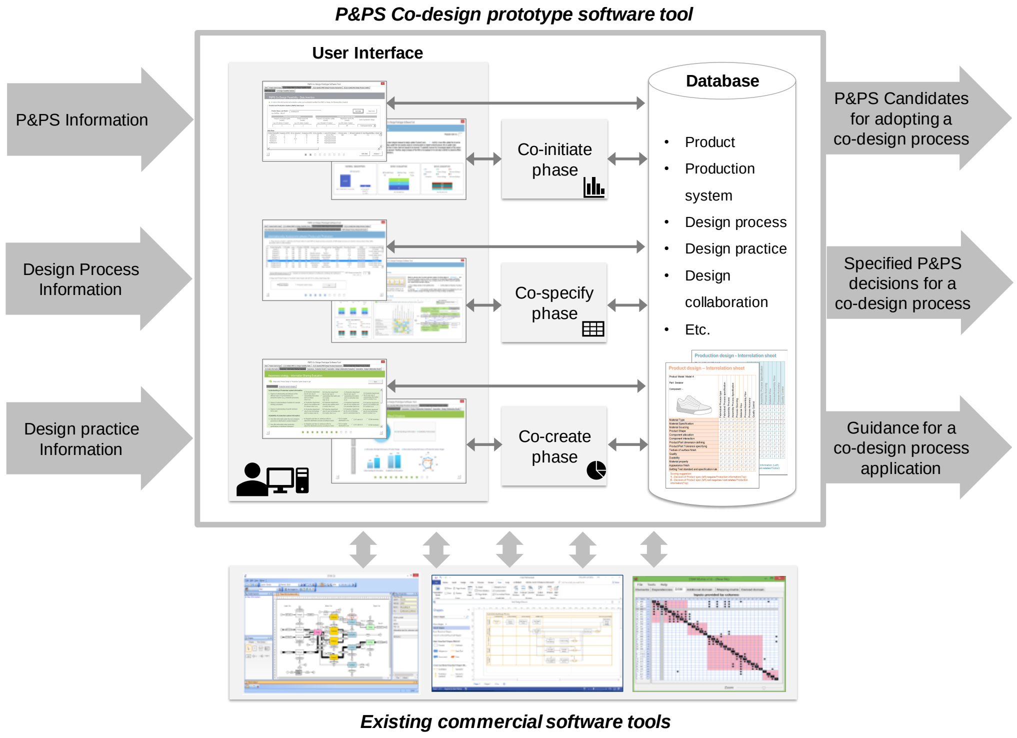


*Figure 10.2 – Overview of PPC software tool*

A flowchart outlining the various functions of PPC provided in Figure 10.3. This start by collecting data related to a Frequency of Product Design (FPD) update, a Frequency of Production System Design (FPSD) update, product lifespan and resource consumption.

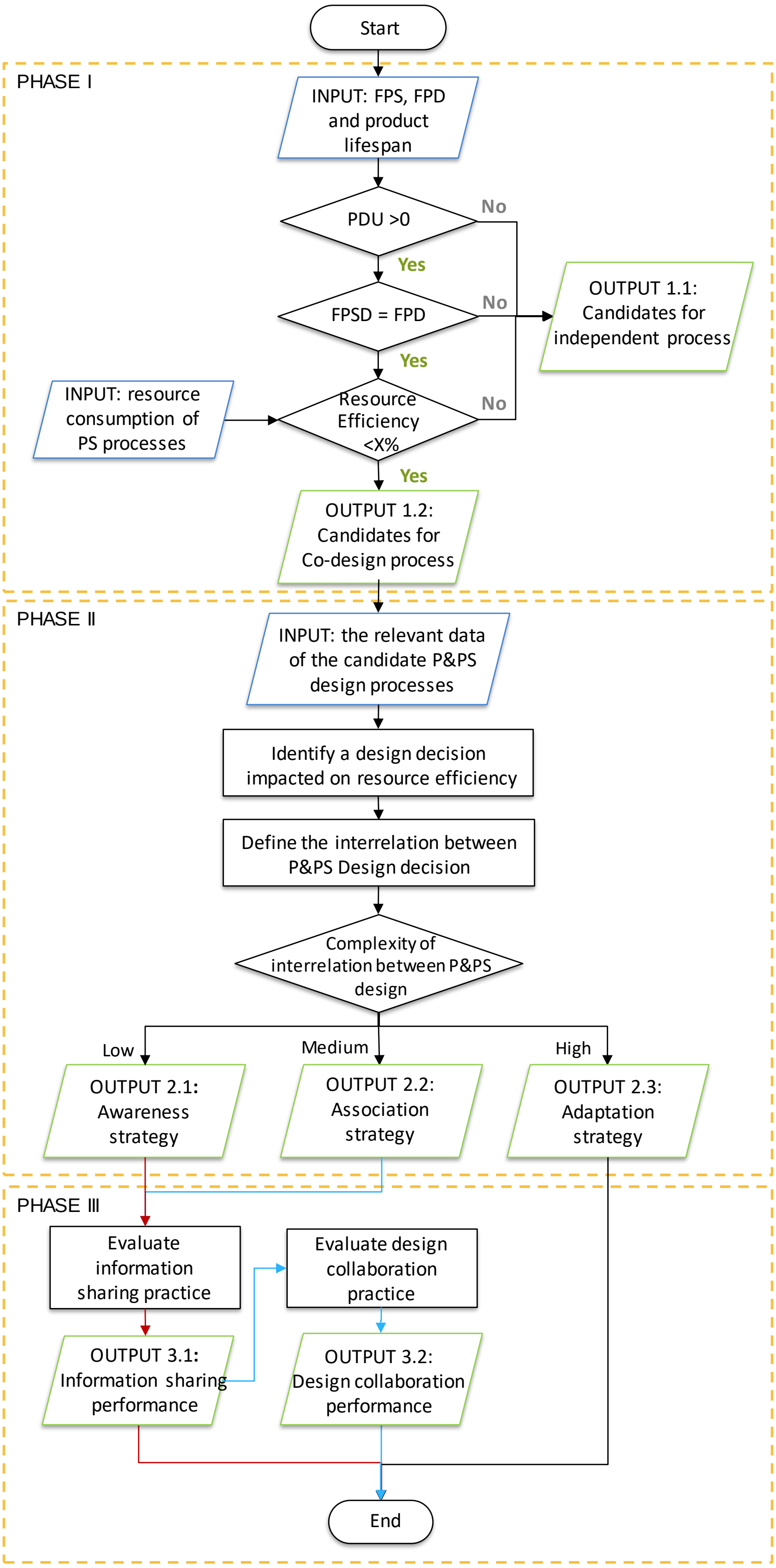


*Figure 10.3 - A flowchart representing the algorithm of the P&PS Co-design prototype software*

This data is used to generate the primary results from Co-initiate phase, namely a recommendation on whether the product and production system under consideration is suitable for a P&PS co-design process. Then, the data related to design process structure and complexity of P&PS design interrelation is used within phase 2 (i.e. Co-specify) to suggest the adoption of one of the Awareness, Associate, or Adaptation strategies in phase 3. Lastly, in the Co-create phase, the analysis of information sharing and collaboration practices between design teams are used to implement the co-design strategies selected in phase 2.

## 10.3 THE PPC SOFTWARE SUPPORT TOOL FOR CO-INITIATE PHASE

Co-initiate phase aims to distinguish most suitable candidates for P&PS co-design process by undertaking five main steps, and listed below:

i. Collection of relevant P&PS design data (Step 1.1)

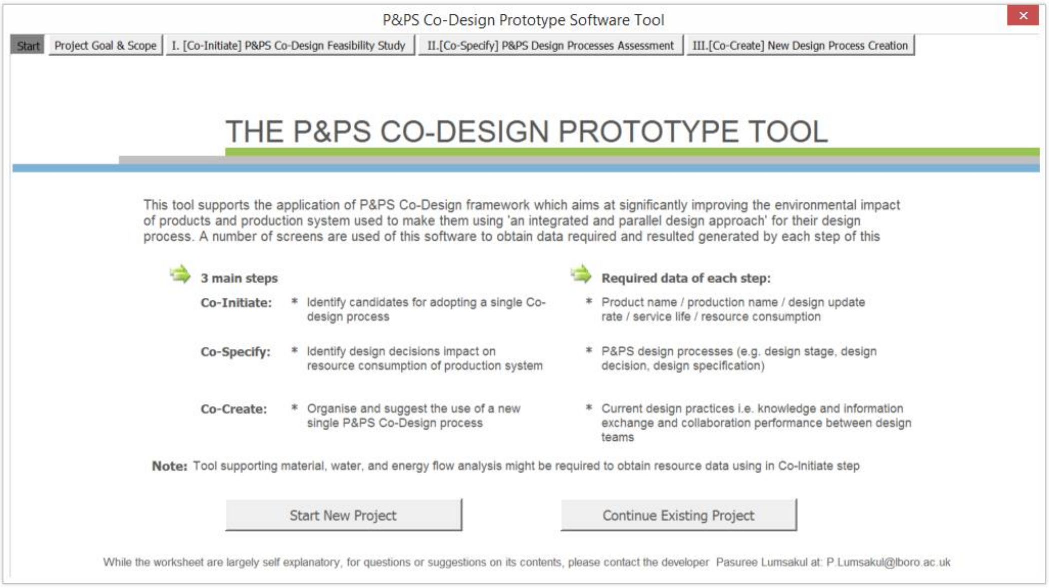
ii. Identifications of a frequency of design updates and interrelation between P&PS design updates (Step 1.2 – 1.3)

iii. Measurement of resource consumption of PS processes (Step 1.4)

iv. Identification of candidates for a P&PS Co-design process (Step 1.5)

### *10.3.1 Collection of relevant P&PS design data (Step1.1)*

Two user interface screens are used to collect relevant P&PS design data. In Figure 10.4, the first screen provides an introduction to P&PS Co-design framework including aim, an overview



THE P&PS CO-DESIGN PROTOTYPE TOOL

This tool supports the application of P&PS Co-Design framework which aims at significantly improving the environmental impact of products and production system used to make them using 'an integrated and parallel design approach' for their design process. A number of screens are used of this software to obtain data required and resulted generated by each step of this

| **3 main steps** | | **Required data of each step:** |
|---|---|---|
| **Co-Initiate:** | * Identify candidates for adopting a single Co-design process | * Product name / production name / design update rate / service life / resource consumption |
| **Co-Specify:** | * Identify design decisions impact on resource consumption of production system | * P&PS design processes (e.g. design stage, design decision, design specification) |
| **Co-Create:** | * Organise and suggest the use of a new single P&PS Co-Design process | * Current design practices i.e. knowledge and information exchange and collaboration performance between design teams |

**Note:** Tool supporting material, water, and energy flow analysis might be required to obtain resource data using in Co-Initiate step

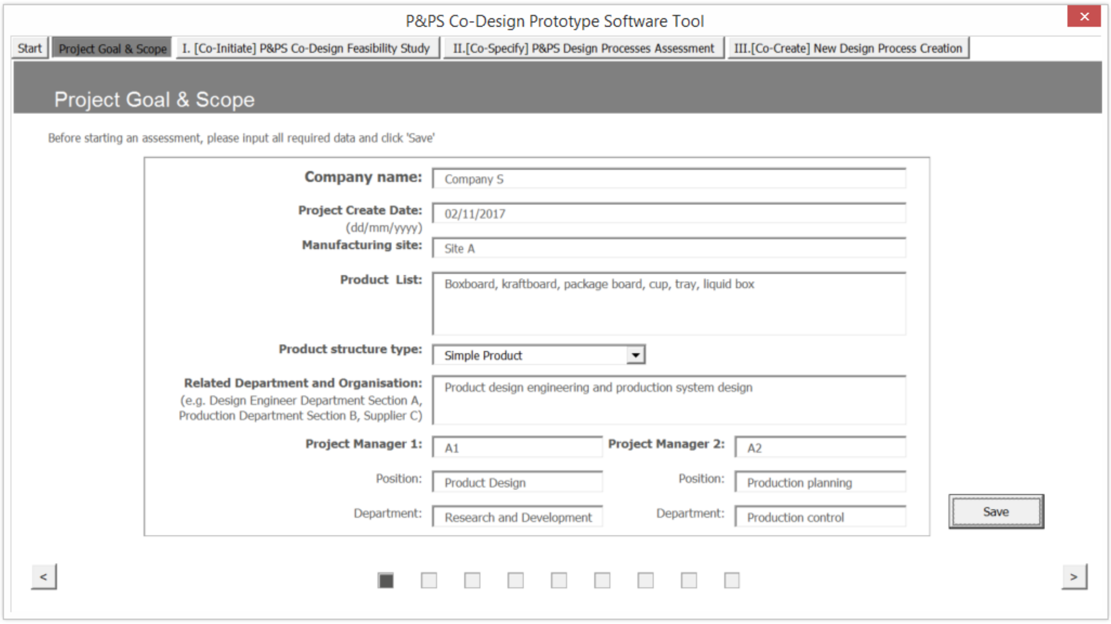
While the worksheet are largely self explanatory, for questions or suggestions on its contents, please contact the developer Pasuree Lumsakul at: P.Lumsakul@lboro.ac.uk

*Figure 10.4 – Start screen of the P&PS Co-design prototype software tool*

three main steps and the required data. Within this screen, a user can click the 'Start New Project' button to begin the implementation of the framework or 'Continue Existing Project' button to recall and continue a stored Co-design project. The second screen (see **Error! Reference source not found.**) facilitates the collection of initial relevant data such as project name/identity, duration, goal and scope, product list and person in charge of the project as well as other related project stakeholders.

### *10.3.2 Identifications of a frequency of design update and interrelation between P&PS design update (Step 1.2 – 1.3)*

The frequency of design updates and interrelation between P&PS design updates are assessed using a Co-initiate data inventory screen (see Figure 10.5). At this step, a Co-design operator can input P&PS data for the first product under consideration including name, product model code, FPD and FPSD updates and product service life. Then, this data is then used to determine the rate of product design using the Equations 8.1 and the relationship between P&PS design updates (see Section 8.2.2 and 8.2.3) to select only those suitable product candidates for P&PS co-design process for further considerations (see Figure 10.6).



Before starting an assessment, please input all required data and click 'Save'

**Company name:** Company S

**Project Create Date:** (dd/mm/yyyy) 02/11/2017

**Manufacturing site:** Site A

**Product List:** Boxboard, kraftboard, package board, cup, tray, liquid box

**Product structure type:** Simple Product

**Related Department and Organisation:** (e.g. Design Engineer Department Section A, Production Department Section B, Supplier C) Product design engineering and production system design

**Project Manager 1:** A1

Position: Product Design

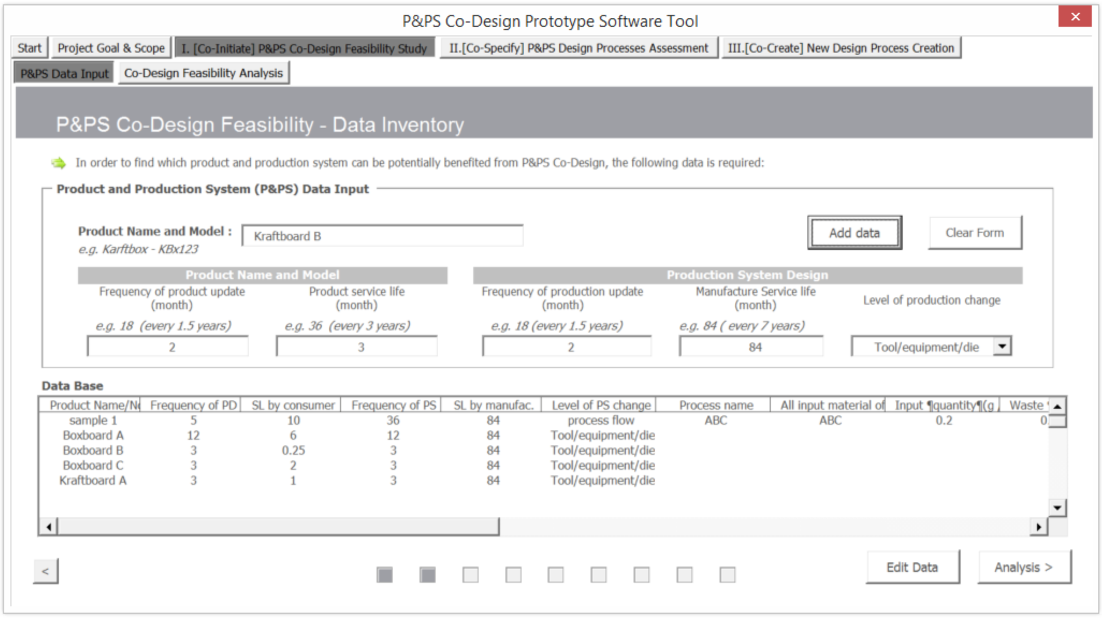
Department: Research and Development

**Project Manager 2:** A2

Position: Production planning

Department: Production control

*Figure 10.5 – A screenshot of the project's goal and scope*



P&PS Co-Design Feasibility - Data Inventory

In order to find which product and production system can be potentially benefited from P&PS Co-Design, the following data is required:

**Product and Production System (P&PS) Data Input**

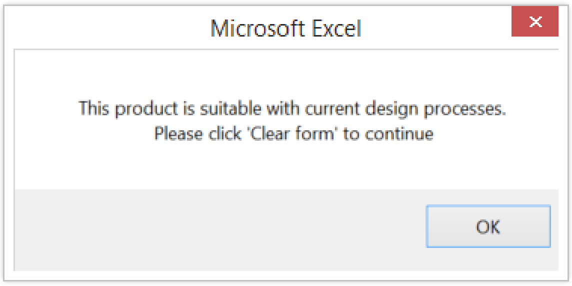
**Product Name and Model :** Kraftboard B
*e.g. Karftbox - KBx123*

| Product Name and Model | | Production System Design | | |
|---|---|---|---|---|
| Frequency of product update (month) | Product service life (month) | Frequency of production update (month) | Manufacture Service life (month) | Level of production change |
| *e.g. 18 (every 1.5 years)* | *e.g. 36 (every 3 years)* | *e.g. 18 (every 1.5 years)* | *e.g. 84 ( every 7 years)* | |
| 2 | 3 | 2 | 84 | Tool/equipment/die |

**Data Base**

| Product Name/N | Frequency of PD | SL by consumer | Frequency of PS | SL by manufac. | Level of PS change | Process name | All input material of | Input ¶quantity¶(g | Waste |
|---|---|---|---|---|---|---|---|---|---|
| sample 1 | 5 | 10 | 36 | 84 | process flow | ABC | ABC | 0.2 | 0 |
| Boxboard A | 12 | 6 | 12 | 84 | Tool/equipment/die | | | | |
| Boxboard B | 3 | 0.25 | 3 | 84 | Tool/equipment/die | | | | |
| Boxboard C | 3 | 2 | 3 | 84 | Tool/equipment/die | | | | |
| Kraftboard A | 3 | 1 | 3 | 84 | Tool/equipment/die | | | | |

*Figure 10.6 - A screenshot of the Co-initiate data inventory*

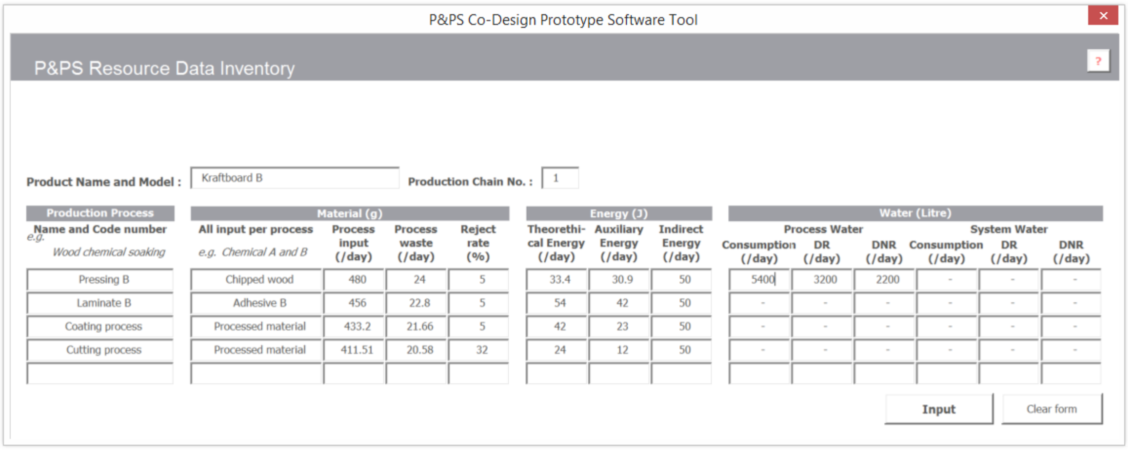


This product is suitable with current design processes.
Please click 'Clear form' to continue

*Figure 10.7 – A screenshot of the result of step 1.2 and 1.3 (when a co-design process is not suitable for a particular design)*

### *10.3.3 Measurement of resource consumption of PS processes (Step 1.4)*

At this step, the resource (energy, material and water) consumption and process waste (material and water waste) of the existing production system is calculated to identify candidates for a co-design process. To achieve this, in Figure 10.8, the 'resource consumption data inventory' screen is used to collect relevant resource consumption data (i.e. percentages of material consumption, material waste, energy consumption and wastewater) for critical production processes. Notably, it is suggested to complete the P&PS data input of all products under consideration (by repeating step 1.2 – 1.4) before continuing to Co-design feasibility analysis. As a result, if data related to resource consumption is not available (held by the company) or cannot be directly (empirically) measured, A resource flow analysis (using a suitable modelling tool) is required to measure input and output resources for each production process. This study utilises the STAN process simulation



**Product Name and Model :** Kraftboard B **Production Chain No. :** 1

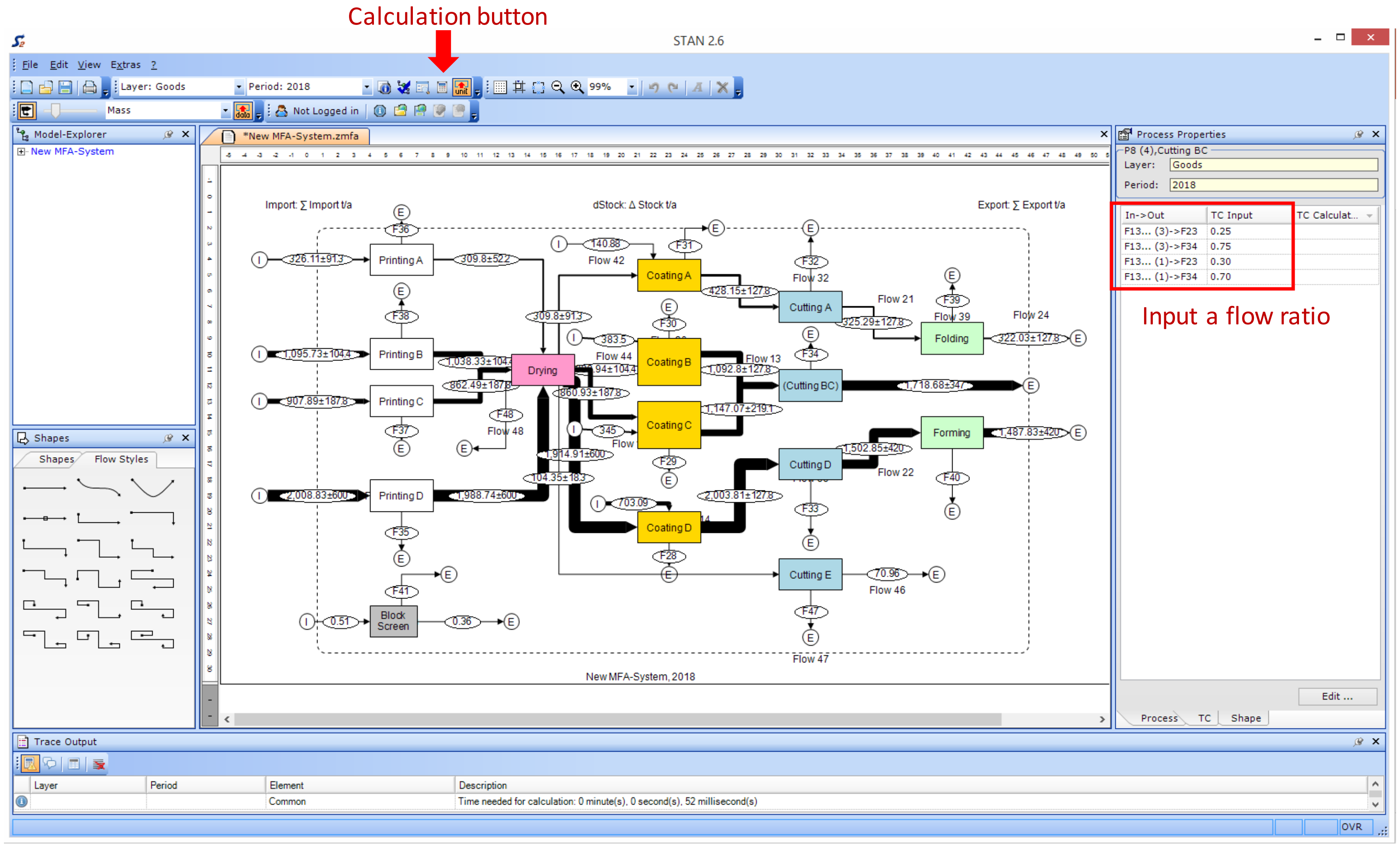
| Production Process | Material (g) | | | | Energy (J) | | | Water (Litre) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Name and Code number | All input per process | Process input (/day) | Process waste (/day) | Reject rate (%) | Theorethi-cal Energy (/day) | Auxiliary Energy (/day) | Indirect Energy (/day) | Process Water | | | System Water | | |
| e.g. Wood chemical soaking | e.g. Chemical A and B | | | | | | | Consumption (/day) | DR (/day) | DNR (/day) | Consumption (/day) | DR (/day) | DNR (/day) |
| Pressing B | Chipped wood | 480 | 24 | 5 | 33.4 | 30.9 | 50 | 5400 | 3200 | 2200 | - | - | - |
| Laminate B | Adhesive B | 456 | 22.8 | 5 | 54 | 42 | 50 | - | - | - | - | - | - |
| Coating process | Processed material | 433.2 | 21.66 | 5 | 42 | 23 | 50 | - | - | - | - | - | - |
| Cutting process | Processed material | 411.51 | 20.58 | 32 | 24 | 12 | 50 | - | - | - | - | - | - |
| | | | | | | | | | | | | | |

*Figure 10.8 – A screenshot of resource consumption data inventory*

software tool to generate simulated data for resource consumption. For an example of a packaging production system in Figure 10.9, the outputs of the cutting process BC can be estimated through two main steps. The former step is to create a material flow of this production system by a) selecting shapes and flows within the ‘Shapes’ frame and b) assigning the available data (e.g. process name, input material, a quantity of input and/or output material and waste ratio) to each production process through a ‘Flow Properties’ frame. Then, the latter is to click the ‘Calculation’ button to allow the software determining the output of this process automatically.

### *10.3.4 Identification of candidates for a P&PS Co-design process (Step 1.5)*

After the completion of P&PS data input, the result of candidates for a P&PS Co-design process is presented in ‘P&PS Co-design feasibility analysis’ screen, as depicted in Figure 10.10, which summarises the Co-initiate results. Further detailed result for each product can be obtained using the ‘detail result screen’ (see Figure 10.11) by clicking ‘Product name’, ‘Select product’ and ‘Result’ button respectively. This screen provides a detail explanation of the result for a company, highlighting whether it should adopt a new co-design process or continue to use their existing independent design processes.


Calculation button

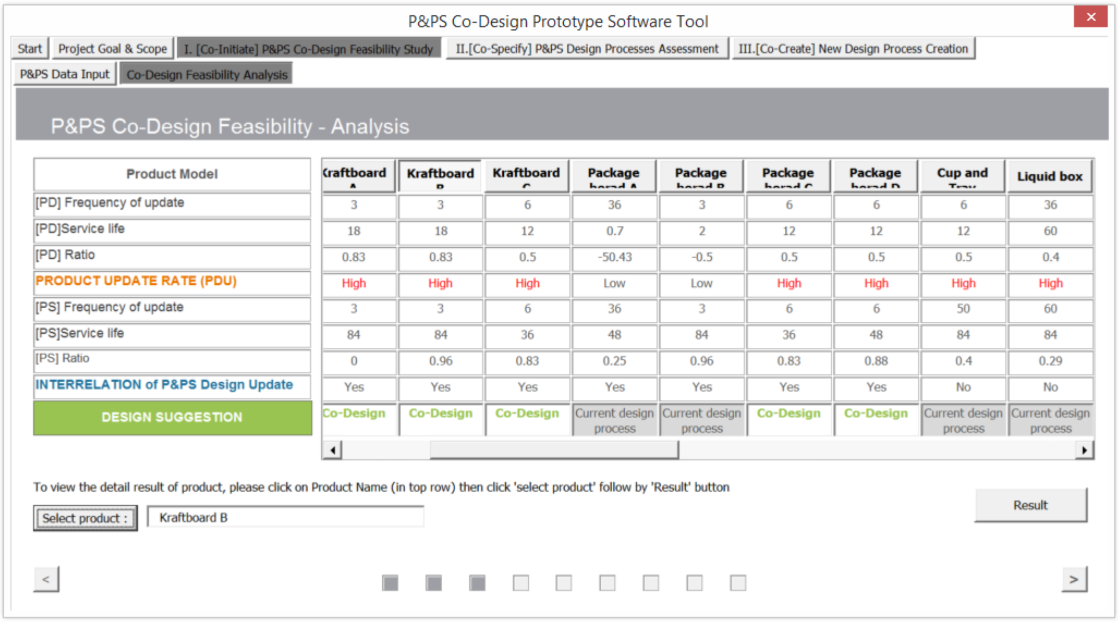
Input a flow ratio

P8 (4),Cutting BC
Layer: Goods
Period: 2018

| In->Out | TC Input | TC Calculat... |
|---|---|---|
| F13... (3)->F23 | 0.25 | |
| F13... (3)->F34 | 0.75 | |
| F13... (1)->F23 | 0.30 | |
| F13... (1)->F34 | 0.70 | |

| Layer | Period | Element | Description |
|---|---|---|---|
| | | Common | Time needed for calculation: 0 minute(s), 0 second(s), 52 millisecond(s) |

*Figure 10.9 - A screenshot of material flow simulation used the STAN2.6 software tool*



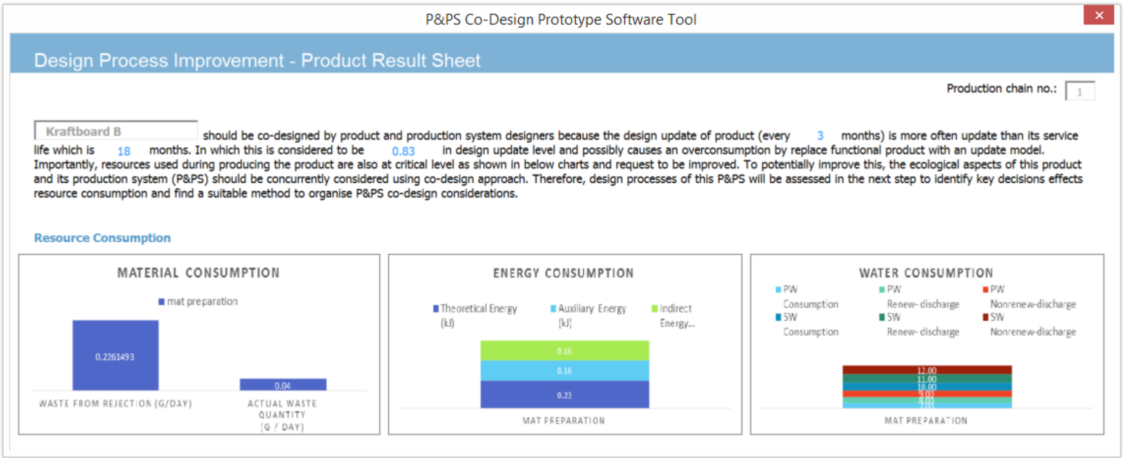
P&PS Co-Design Feasibility - Analysis

| Product Model | raftboard A | Kraftboard B | Kraftboard C | Package board A | Package board B | Package board C | Package board D | Cup and Tray | Liquid box |
|---|---|---|---|---|---|---|---|---|---|
| [PD] Frequency of update | 3 | 3 | 6 | 36 | 3 | 6 | 6 | 6 | 36 |
| [PD]Service life | 18 | 18 | 12 | 0.7 | 2 | 12 | 12 | 12 | 60 |
| [PD] Ratio | 0.83 | 0.83 | 0.5 | -50.43 | -0.5 | 0.5 | 0.5 | 0.5 | 0.4 |
| PRODUCT UPDATE RATE (PDU) | High | High | High | Low | Low | High | High | High | High |
| [PS] Frequency of update | 3 | 3 | 6 | 36 | 3 | 6 | 6 | 50 | 60 |
| [PS]Service life | 84 | 84 | 36 | 48 | 84 | 36 | 48 | 84 | 84 |
| [PS] Ratio | 0 | 0.96 | 0.83 | 0.25 | 0.96 | 0.83 | 0.88 | 0.4 | 0.29 |
| INTERRELATION of P&PS Design Update | Yes | Yes | Yes | Yes | Yes | Yes | Yes | No | No |
| DESIGN SUGGESTION | Co-Design | Co-Design | Co-Design | Current design process | Current design process | Co-Design | Co-Design | Current design process | Current design process |

To view the detail result of product, please click on Product Name (in top row) then click 'select product' follow by 'Result' button

Select product : Kraftboard B

*Figure 10.10 - A screenshot of the Co-design feasibility analysis result*



Design Process Improvement - Product Result Sheet

Production chain no.: 1

Kraftboard B should be co-designed by product and production system designers because the design update of product (every 3 months) is more often update than its service life which is 18 months. In which this is considered to be 0.83 in design update level and possibly causes an overconsumption by replace functional product with an update model. Importantly, resources used during producing the product are also at critical level as shown in below charts and request to be improved. To potentially improve this, the ecological aspects of this product and its production system (P&PS) should be concurrently considered using co-design approach. Therefore, design processes of this P&PS will be assessed in the next step to identify key decisions effects resource consumption and find a suitable method to organise P&PS co-design considerations.

Resource Consumption

*Figure 10.11 - A screenshot of the Co-design feasibility detail result of each product design*

## 10.4 THE PPC SOFTWARE SUPPORT TOOL FOR CO-SPECIFY PHASE

Similarly, the application of the Co-specify phase can be achieved through the four steps, as listed below:

i. Interrelation assessment between product parts and/or subassemblies (Step 2.0)

ii. The identifications of design decisions which impact on resource consumption and the interrelation between these P&PS design decisions (Step 2.1 – 2.2)

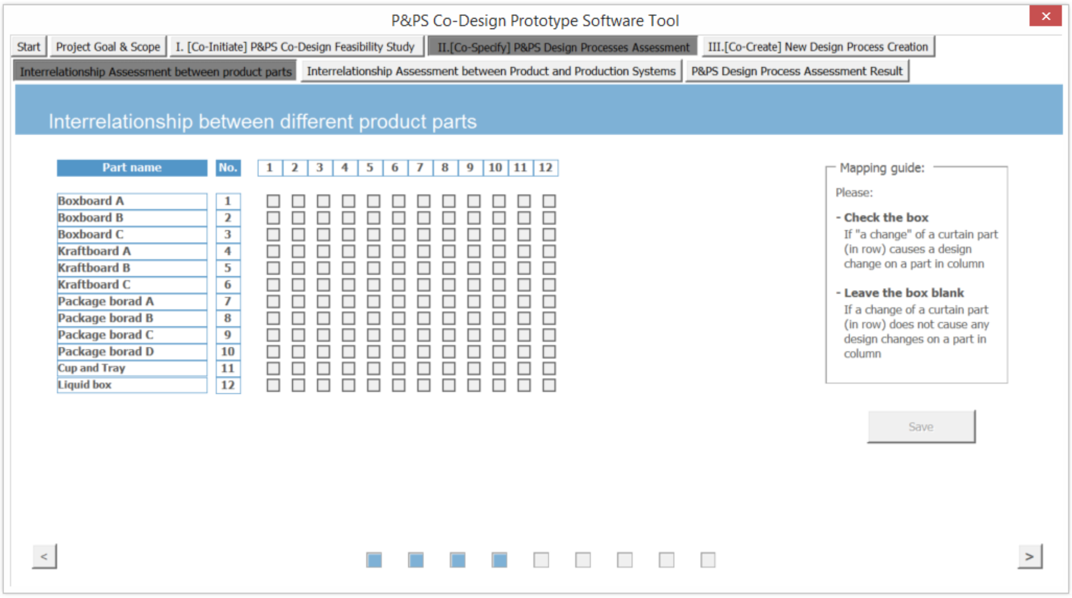
iii. Recommendation of the suitable strategy for applying co-design (Step 2.3)

### *10.4.1 Interrelation assessment between product parts (Step 2.0)*

As outlined in Section 8.3.1, in a case of a complex product, any changes or improvements in a part (sub-assembly) design for reducing resource consumption may result in consequential changes in other part/subassembly designs. Hence, the ‘interrelationship assessment 1’ screen, shown in Figure 10.12, is used to assess the interrelation between a product’s parts/subassemblies. The PPC software tool guides the user to select a checkbox (☑) if design changes to parts listed in the rows cause a design change on parts listed in the columns or leave it blank if there is no relationship between parts design changes.

### *10.4.2 The identifications of design decisions which impact on resource consumption and the interrelation between P&PS design decisions (Step 2.1 – 2.2)*

This step starts at ‘interrelation assessment 2’ screen (See Figure10.13) which is used for navigating a user to select input data related to a set of design processes by entering the names of all products which shared this set of design processes and an identification number for these design processes. Then, the identifications of design decisions which impact on resource consumption and the interrelation between P&PS design decisions are accomplished through ‘decision allocation’, ‘ecological identification’ and ‘design interrelation’ screens as depicted in Figure 10.14. These screens are used to identify when design decisions are made, to categorise which decisions impact on the improvement of resource efficiency and to assess an interrelation between PD and PSD decisions, respectively.



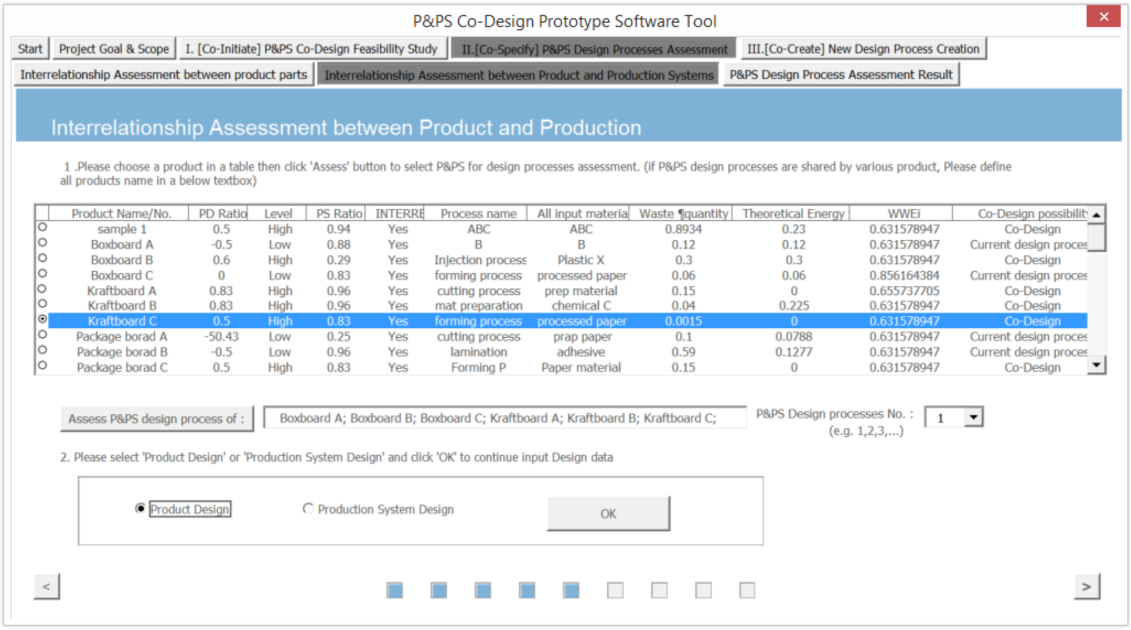
| Part name | No. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Boxboard A | 1 | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Boxboard B | 2 | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Boxboard C | 3 | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Kraftboard A | 4 | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Kraftboard B | 5 | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Kraftboard C | 6 | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Package borad A | 7 | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Package borad B | 8 | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Package borad C | 9 | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Package borad D | 10 | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Cup and Tray | 11 | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Liquid box | 12 | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |

Mapping guide:

Please:

- **Check the box**
  If "a change" of a curtain part (in row) causes a design change on a part in column
- **Leave the box blank**
  If a change of a curtain part (in row) does not cause any design changes on a part in column

*Figure 10.12 - A screenshot of the product part interrelation assessment*



1 .Please choose a product in a table then click 'Assess' button to select P&PS for design processes assessment. (if P&PS design processes are shared by various product, Please define all products name in a below textbox)

| | Product Name/No. | PD Ratio | Level | PS Ratio | INTERRE | Process name | All input materia | Waste ¶quantity | Theoretical Energy | WWEi | Co-Design possibilit |
|---|---|---|---|---|---|---|---|---|---|---|---|
| ○ | sample 1 | 0.5 | High | 0.94 | Yes | ABC | ABC | 0.8934 | 0.23 | 0.631578947 | Co-Design |
| ○ | Boxboard A | -0.5 | Low | 0.88 | Yes | B | B | 0.12 | 0.12 | 0.631578947 | Current design proces |
| ○ | Boxboard B | 0.6 | High | 0.29 | Yes | Injection process | Plastic X | 0.3 | 0.3 | 0.631578947 | Co-Design |
| ○ | Boxboard C | 0 | Low | 0.83 | Yes | forming process | processed paper | 0.06 | 0.06 | 0.856164384 | Current design proces |
| ○ | Kraftboard A | 0.83 | High | 0.96 | Yes | cutting process | prep material | 0.15 | 0 | 0.655737705 | Co-Design |
| ○ | Kraftboard B | 0.83 | High | 0.96 | Yes | mat preparation | chemical C | 0.04 | 0.225 | 0.631578947 | Co-Design |
| ◉ | Kraftboard C | 0.5 | High | 0.83 | Yes | forming process | processed paper | 0.0015 | 0 | 0.631578947 | Co-Design |
| ○ | Package borad A | -50.43 | Low | 0.25 | Yes | cutting process | prap paper | 0.1 | 0.0788 | 0.631578947 | Current design proces |
| ○ | Package borad B | -0.5 | Low | 0.96 | Yes | lamination | adhesive | 0.59 | 0.1277 | 0.631578947 | Current design proces |
| ○ | Package borad C | 0.5 | High | 0.83 | Yes | Forming P | Paper material | 0.15 | 0 | 0.631578947 | Co-Design |

Assess P&PS design process of : Boxboard A; Boxboard B; Boxboard C; Kraftboard A; Kraftboard B; Kraftboard C;

P&PS Design processes No. : 1
(e.g. 1,2,3,...)

2. Please select 'Product Design' or 'Production System Design' and click 'OK' to continue input Design data

● Product Design ○ Production System Design

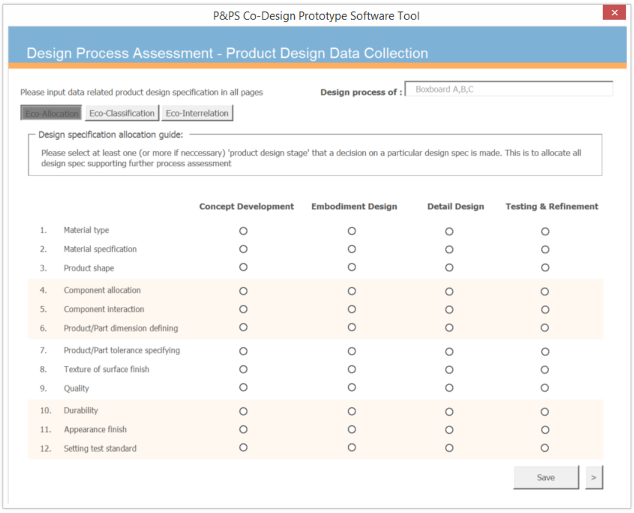
*Figure 10.13 - A screenshot of the interrelation assessment between P&PS design processes*

For example, on the design interrelation for product design screen, a product designer is advised to select a checkbox (☑) if the availability of the relevant information for a PSD process is required to support decision making for a particular PD process or to leave it blank if PSD information is not needed. Notably, if a particular design decision has been identified in the previous step to have no impact on resource consumption, this decision will not be enabled for the design interrelation assessment. For instance, in Figure 10.15, component interaction and finished surface are not included in the assessment since these decisions do not influence any resource consumption.

### *10.4.3 Recommendation of the suitable strategy for applying co-design (Step 2.3)*

In this step, the result of the assessments, which is determined based on the analysis outlined in Section 8.3.4, is summarised in ‘P&PS design process assessment result’ screen (See Figure 10.16). The PPC user is guided to select a particular product design from the provided table and click ‘view result’ button to open ‘a design process improvement’ screen, as shown in Figure 10.17. This screen is used as an information dashboard and is divided into three frames (sections), each of which presents the results related to one of the Co-initiate, Co-specify and Co-create phase. For instance, ‘Co-design Creation Strategy’ frame portrays the recommended strategy for P&PS design processes which is determined to be the most suitable Co-create strategy based on the input design process data and the results of interrelation assessment.

Decision-Allocation



P&PS Co-Design Prototype Software Tool

Design Process Assessment - Product Design Data Collection

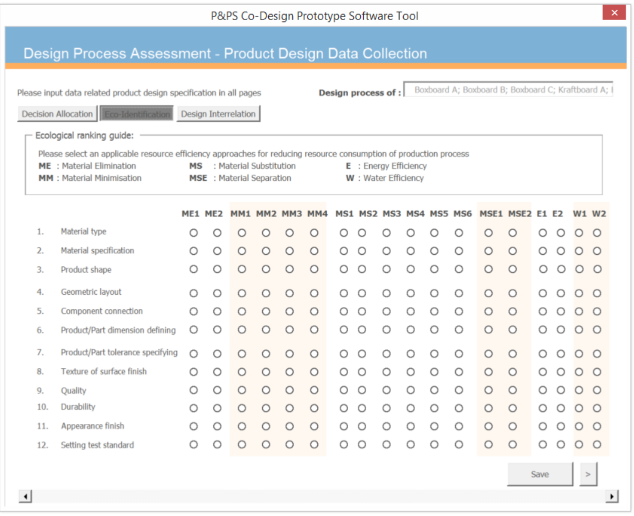
Please input data related product design specification in all pages **Design process of :** Boxboard A,B,C

Design specification allocation guide:

Please select at least one (or more if neccessary) 'product design stage' that a decision on a particular design spec is made. This is to allocate all design spec supporting further process assessment

| | **Concept Development** | **Embodiment Design** | **Detail Design** | **Testing & Refinement** |
|---|---|---|---|---|
| 1. Material type | ○ | ○ | ○ | ○ |
| 2. Material specification | ○ | ○ | ○ | ○ |
| 3. Product shape | ○ | ○ | ○ | ○ |
| 4. Component allocation | ○ | ○ | ○ | ○ |
| 5. Component interaction | ○ | ○ | ○ | ○ |
| 6. Product/Part dimension defining | ○ | ○ | ○ | ○ |
| 7. Product/Part tolerance specifying | ○ | ○ | ○ | ○ |
| 8. Texture of surface finish | ○ | ○ | ○ | ○ |
| 9. Quality | ○ | ○ | ○ | ○ |
| 10. Durability | ○ | ○ | ○ | ○ |
| 11. Appearance finish | ○ | ○ | ○ | ○ |
| 12. Setting test standard | ○ | ○ | ○ | ○ |

Eco-Identification



P&PS Co-Design Prototype Software Tool

Design Process Assessment - Product Design Data Collection

Please input data related product design specification in all pages **Design process of :** Boxboard A; Boxboard B; Boxboard C; Kraftboard A;

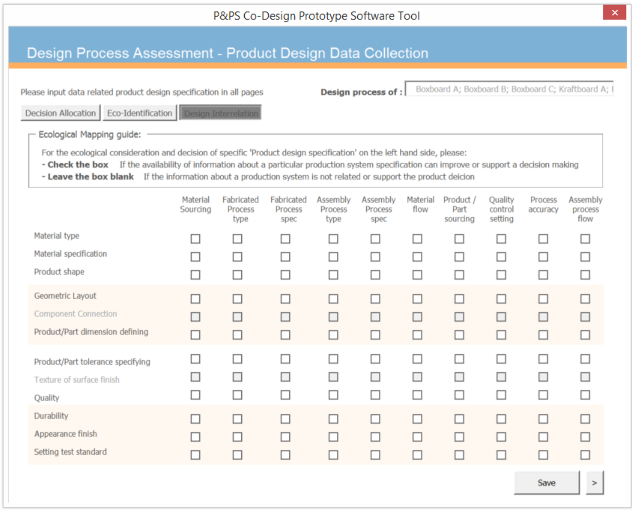
Ecological ranking guide:

Please select an applicable resource efficiency approaches for reducing resource consumption of production process

**ME** : Material Elimination
**MM** : Material Minimisation
**MS** : Material Substitution
**MSE** : Material Separation
**E** : Energy Efficiency
**W** : Water Efficiency

| | **ME1** | **ME2** | **MM1** | **MM2** | **MM3** | **MM4** | **MS1** | **MS2** | **MS3** | **MS4** | **MS5** | **MS6** | **MSE1** | **MSE2** | **E1** | **E2** | **W1** | **W2** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1. Material type | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| 2. Material specification | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| 3. Product shape | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| 4. Geometric layout | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| 5. Component connection | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| 6. Product/Part dimension defining | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| 7. Product/Part tolerance specifying | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| 8. Texture of surface finish | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| 9. Quality | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| 10. Durability | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| 11. Appearance finish | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| 12. Setting test standard | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ |

P&PS Design Interrelation



P&PS Co-Design Prototype Software Tool

Design Process Assessment - Product Design Data Collection

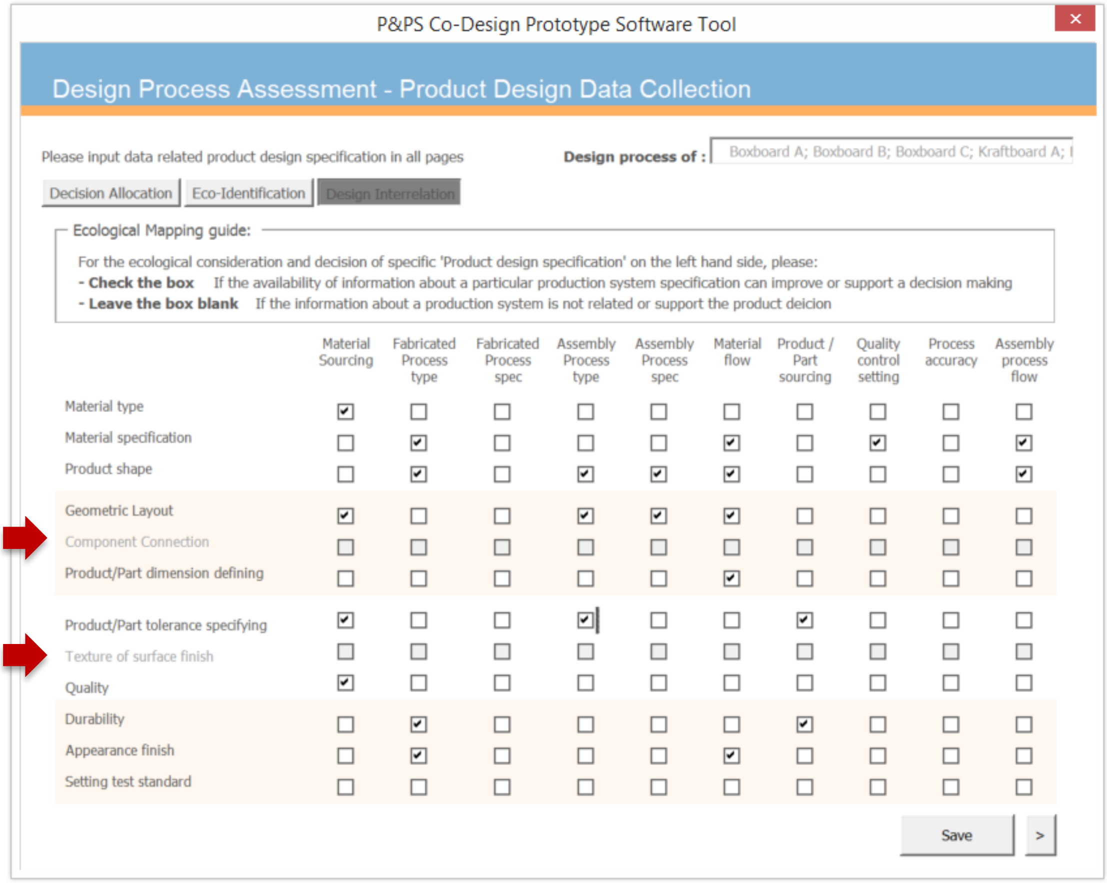
Please input data related product design specification in all pages **Design process of :** Boxboard A; Boxboard B; Boxboard C; Kraftboard A;

Ecological Mapping guide:

For the ecological consideration and decision of specific 'Product design specification' on the left hand side, please:
- **Check the box** If the availability of information about a particular production system specification can improve or support a decision making
- **Leave the box blank** If the information about a production system is not related or support the product deicion

| | Material Sourcing | Fabricated Process type | Fabricated Process spec | Assembly Process type | Assembly Process spec | Material flow | Product / Part sourcing | Quality control setting | Process accuracy | Assembly process flow |
|---|---|---|---|---|---|---|---|---|---|---|
| Material type | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Material specification | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Product shape | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Geometric Layout | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Component Connection | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Product/Part dimension defining | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Product/Part tolerance specifying | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Texture of surface finish | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Quality | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Durability | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Appearance finish | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Setting test standard | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |

Figure 10.14 - An overview of P&PS Design process assessments (Design decision allocation, Eco-Identification, Design interrelation)



Please input data related product design specification in all pages

**Design process of :** Boxboard A; Boxboard B; Boxboard C; Kraftboard A; I

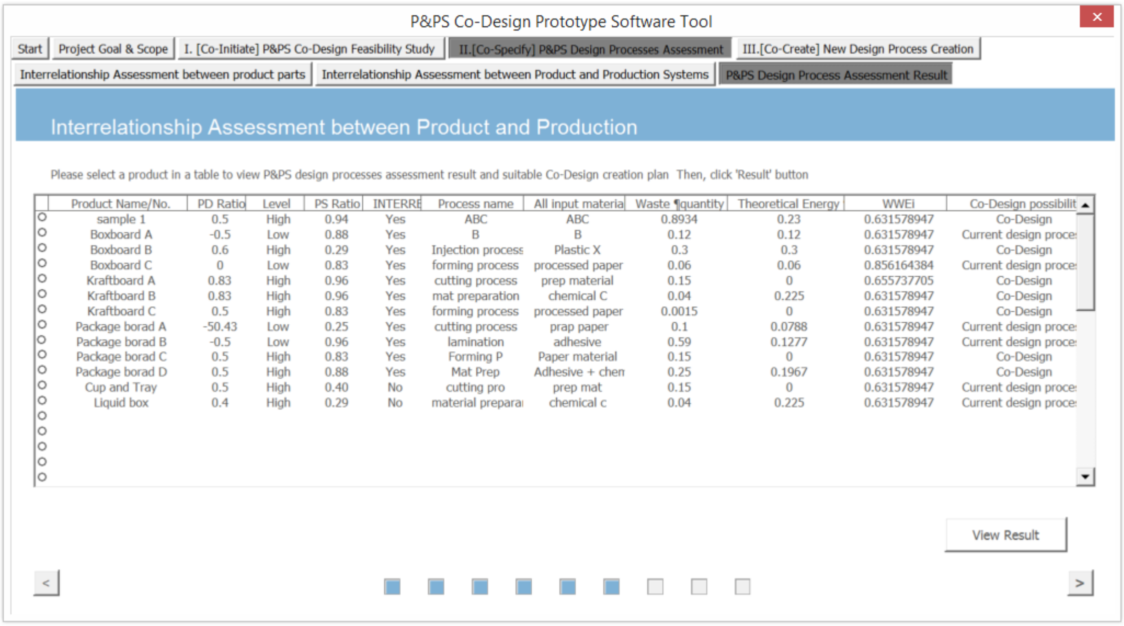
Ecological Mapping guide:

For the ecological consideration and decision of specific 'Product design specification' on the left hand side, please:

- **Check the box** If the availability of information about a particular production system specification can improve or support a decision making
- **Leave the box blank** If the information about a production system is not related or support the product deicion

| | Material Sourcing | Fabricated Process type | Fabricated Process spec | Assembly Process type | Assembly Process spec | Material flow | Product / Part sourcing | Quality control setting | Process accuracy | Assembly process flow |
|---|---|---|---|---|---|---|---|---|---|---|
| Material type | ☑ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Material specification | ☐ | ☑ | ☐ | ☐ | ☐ | ☑ | ☐ | ☑ | ☐ | ☑ |
| Product shape | ☐ | ☑ | ☐ | ☑ | ☑ | ☑ | ☐ | ☐ | ☐ | ☑ |
| Geometric Layout | ☑ | ☐ | ☐ | ☑ | ☑ | ☑ | ☐ | ☐ | ☐ | ☐ |
| Component Connection | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Product/Part dimension defining | ☐ | ☐ | ☐ | ☐ | ☐ | ☑ | ☐ | ☐ | ☐ | ☐ |
| Product/Part tolerance specifying | ☑ | ☐ | ☐ | ☑ | ☐ | ☐ | ☑ | ☐ | ☐ | ☐ |
| Texture of surface finish | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Quality | ☑ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Durability | ☐ | ☑ | ☐ | ☐ | ☐ | ☐ | ☑ | ☐ | ☐ | ☐ |
| Appearance finish | ☐ | ☑ | ☐ | ☐ | ☐ | ☑ | ☐ | ☐ | ☐ | ☐ |
| Setting test standard | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |

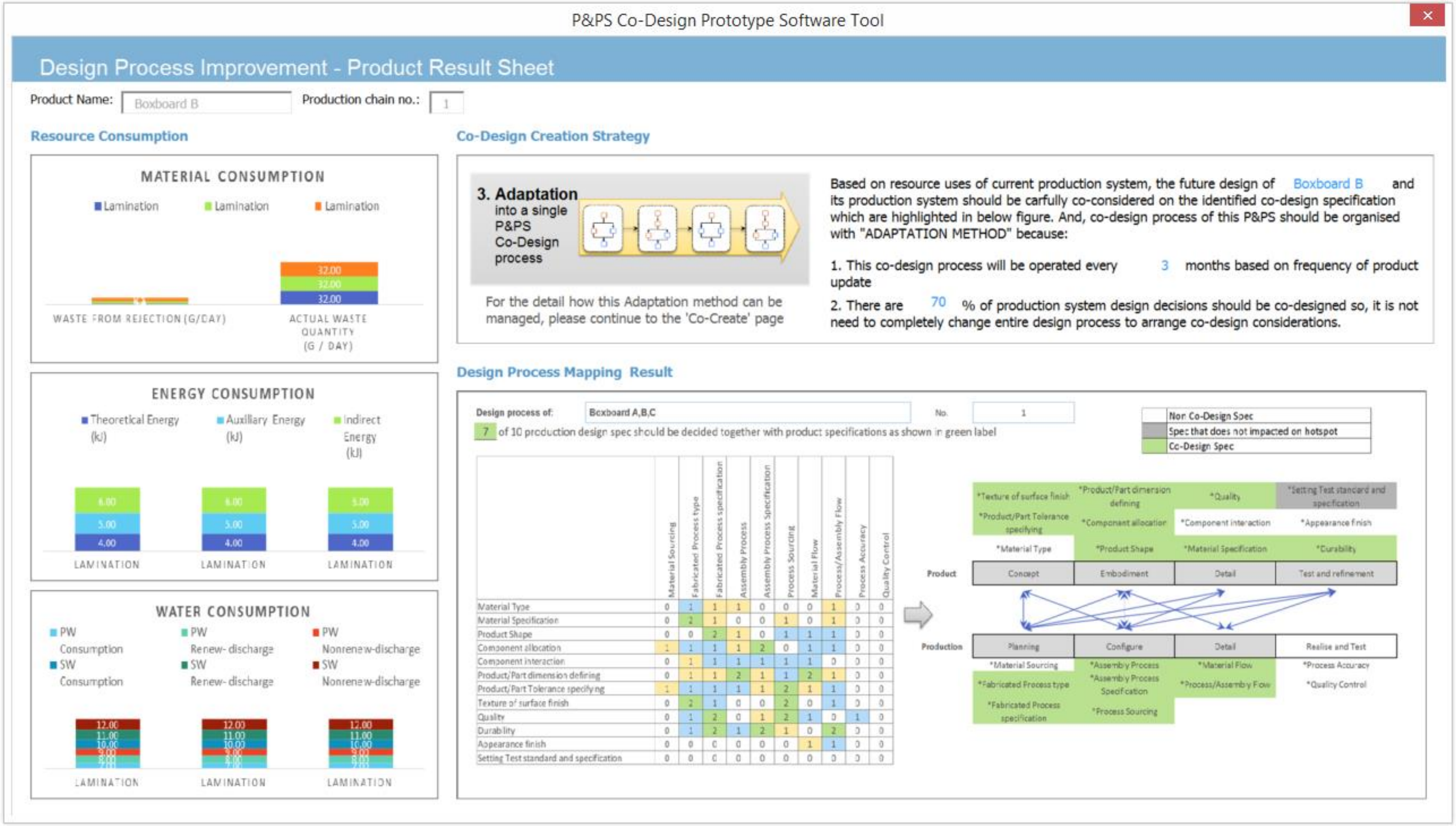
*Figure 10.15 – A screenshot of design-interrelation (an example of a non-enable specification)*



Please select a product in a table to view P&PS design processes assessment result and suitable Co-Design creation plan Then, click 'Result' button

| | Product Name/No. | PD Ratio | Level | PS Ratio | INTERRE | Process name | All input materia | Waste ¶quantity | Theoretical Energy | WWEi | Co-Design possibilit |
|---|---|---|---|---|---|---|---|---|---|---|---|
| ○ | sample 1 | 0.5 | High | 0.94 | Yes | ABC | ABC | 0.8934 | 0.23 | 0.631578947 | Co-Design |
| ○ | Boxboard A | -0.5 | Low | 0.88 | Yes | B | B | 0.12 | 0.12 | 0.631578947 | Current design proce |
| ○ | Boxboard B | 0.6 | High | 0.29 | Yes | Injection process | Plastic X | 0.3 | 0.3 | 0.631578947 | Co-Design |
| ○ | Boxboard C | 0 | Low | 0.83 | Yes | forming process | processed paper | 0.06 | 0.06 | 0.856164384 | Current design proce |
| ○ | Kraftboard A | 0.83 | High | 0.96 | Yes | cutting process | prep material | 0.15 | 0 | 0.655737705 | Co-Design |
| ○ | Kraftboard B | 0.83 | High | 0.96 | Yes | mat preparation | chemical C | 0.04 | 0.225 | 0.631578947 | Co-Design |
| ○ | Kraftboard C | 0.5 | High | 0.83 | Yes | forming process | processed paper | 0.0015 | 0 | 0.631578947 | Co-Design |
| ○ | Package borad A | -50.43 | Low | 0.25 | Yes | cutting process | prap paper | 0.1 | 0.0788 | 0.631578947 | Current design proce |
| ○ | Package borad B | -0.5 | Low | 0.96 | Yes | lamination | adhesive | 0.59 | 0.1277 | 0.631578947 | Current design proce |
| ○ | Package borad C | 0.5 | High | 0.83 | Yes | Forming P | Paper material | 0.15 | 0 | 0.631578947 | Co-Design |
| ○ | Package borad D | 0.5 | High | 0.88 | Yes | Mat Prep | Adhesive + chen | 0.25 | 0.1967 | 0.631578947 | Co-Design |
| ○ | Cup and Tray | 0.5 | High | 0.40 | No | cutting pro | prep mat | 0.15 | 0 | 0.631578947 | Current design proce |
| ○ | Liquid box | 0.4 | High | 0.29 | No | material preparai | chemical c | 0.04 | 0.225 | 0.631578947 | Current design proce |
| ○ | | | | | | | | | | | |
| ○ | | | | | | | | | | | |
| ○ | | | | | | | | | | | |
| ○ | | | | | | | | | | | |
| ○ | | | | | | | | | | | |

*Figure 10.16 – A screenshot of P&PS Design process assessment result*



P&PS Co-Design Prototype Software Tool

Design Process Improvement - Product Result Sheet

Product Name: Boxboard B    Production chain no.: 1

**Resource Consumption**

**Co-Design Creation Strategy**

**3. Adaptation** into a single P&PS Co-Design process

For the detail how this Adaptation method can be managed, please continue to the 'Co-Create' page

Based on resource uses of current production system, the future design of Boxboard B and its production system should be carfully co-considered on the identified co-design specification which are highlighted in below figure. And, co-design process of this P&PS should be organised with "ADAPTATION METHOD" because:

1. This co-design process will be operated every 3 months based on frequency of product update

2. There are 70 % of production system design decisions should be co-designed so, it is not need to completely change entire design process to arrange co-design considerations.

**Design Process Mapping Result**

Design process of: Boxboard A,B,C    No. 1

7 of 10 production design spec should be decided together with product specifications as shown in green label

|  |  |
|---|---|
|  | Non Co-Design Spec |
| ▨ | Spec that does not impacted on hotspot |
| 🟩 | Co-Design Spec |

|  | Material Sourcing | Fabricated Process type | Fabricated Process specification | Assembly Process | Assembly Process Specification | Process Sourcing | Material Flow | Process/Assembly Flow | Process Accuracy | Quality Control |
|---|---|---|---|---|---|---|---|---|---|---|
| Material Type | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 1 | 0 | 0 |
| Material Specification | 0 | 2 | 1 | 0 | 0 | 1 | 0 | 1 | 0 | 0 |
| Product Shape | 0 | 0 | 2 | 1 | 0 | 1 | 1 | 1 | 0 | 0 |
| Component allocation | 1 | 1 | 1 | 1 | 2 | 0 | 1 | 1 | 0 | 0 |
| Component interaction | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 |
| Product/Part dimension defining | 0 | 1 | 1 | 2 | 1 | 1 | 2 | 1 | 0 | 0 |
| Product/Part Tolerance specifying | 1 | 1 | 1 | 1 | 1 | 2 | 1 | 1 | 0 | 0 |
| Texture of surface finish | 0 | 2 | 1 | 0 | 0 | 2 | 0 | 1 | 0 | 0 |
| Quality | 0 | 1 | 2 | 0 | 1 | 2 | 1 | 0 | 1 | 0 |
| Durability | 0 | 1 | 2 | 1 | 2 | 1 | 0 | 2 | 0 | 0 |
| Appearance finish | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 |
| Setting Test standard and specification | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

*Figure 10.17 – A screenshot of Design processes improvement – P&PS Design Processes Result*

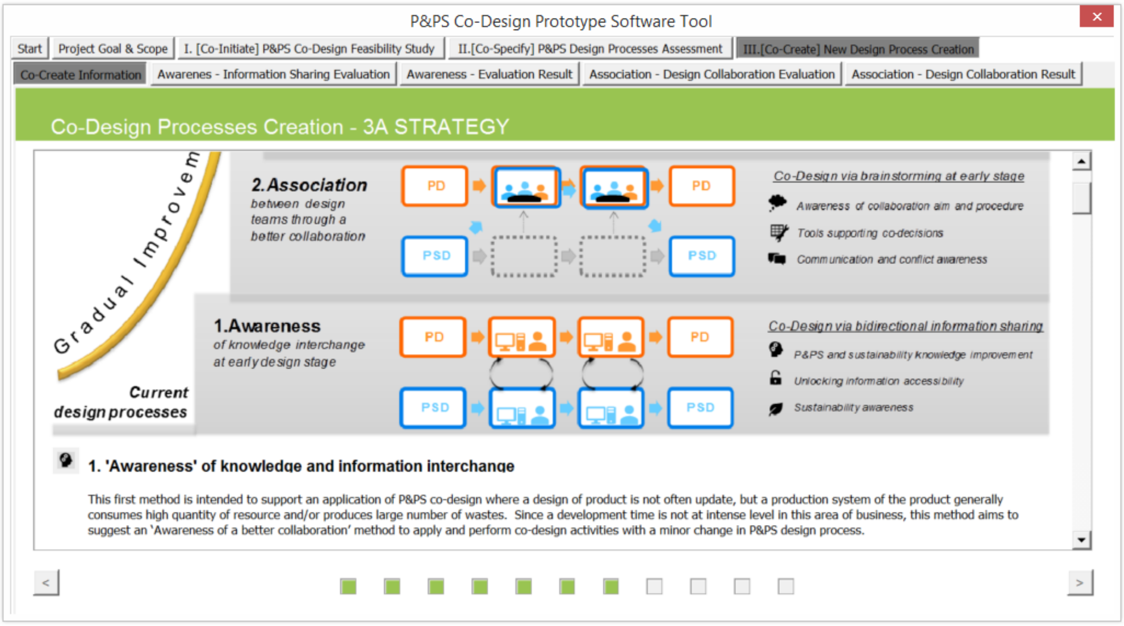
The results of material, energy and water consumption for each production processes are presented in ‘Resource Consumptions’ frame. Moreover, the result of Eco-identification and Design interrelation assessment are summarised in ‘Design Process Mapping Result’ frame in which the co-design decisions highlighted as a ‘green’ tab are suitable for P&PS co-design process. Finally, the links between various product and production system design processes are shown in this information dashboard using the overview of the P&PS design map.

## 10.5 THE PPC SOFTWARE SUPPORT TOOL FOR CO-CREATE PHASE

In the third phase, PPC software tool provides the detailed information for implementing Awareness, Association and Adaptation strategy within ‘Co-create Information’ screen (see Figure 10.18). The remaining subsections of this chapter explain how the applications of these strategies are supported by PPC software and other commercial software tools.

### *10.5.1 Awareness strategy*

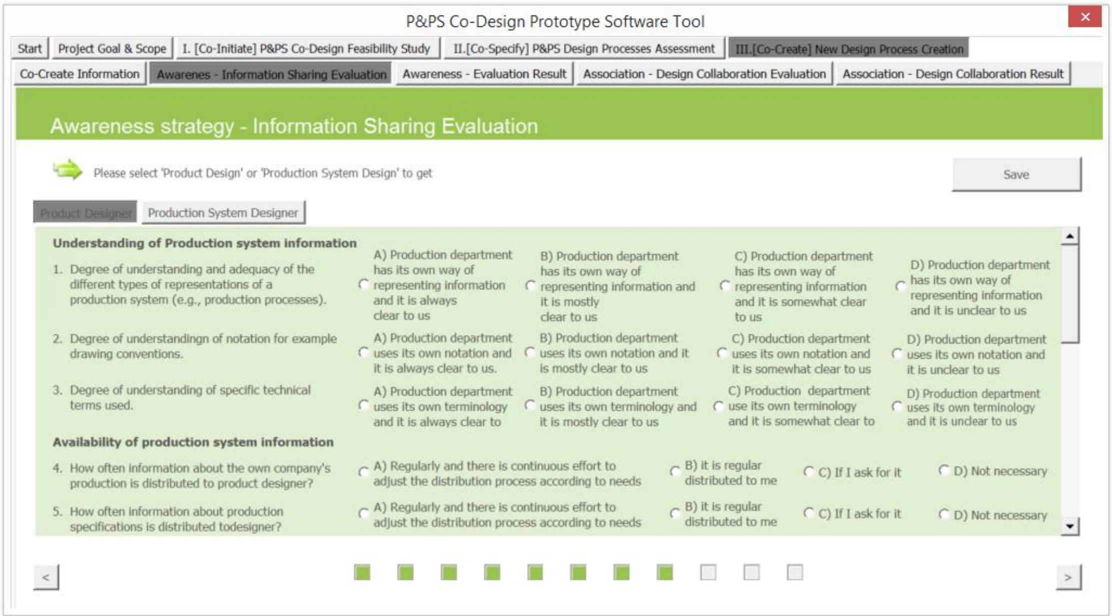
The implementation of Awareness strategy necessitates the improvement of P&PS design information sharing between teams and knowledge of sustainability and resource efficiency. The information sharing evaluation checklist outlined in Table 9.2 and 9.3 are provided in ‘Information Sharing Evaluation’ screen (see Figure 10.19). In this screen, data related to the current information sharing practice is entered and analysed, the results of which are presented in ‘knowledge and information sharing evaluation’ screen, as shown in Figure 10.20.



1. 'Awareness' of knowledge and information interchange

This first method is intended to support an application of P&PS co-design where a design of product is not often update, but a production system of the product generally consumes high quantity of resource and/or produces large number of wastes. Since a development time is not at intense level in this area of business, this method aims to suggest an ‘Awareness of a better collaboration’ method to apply and perform co-design activities with a minor change in P&PS design process.

*Figure 10.18 – A screenshot of Co-create strategy*



Awareness strategy - Information Sharing Evaluation

Please select 'Product Design' or 'Production System Design' to get

**Understanding of Production system information**

1. Degree of understanding and adequacy of the different types of representations of a production system (e.g., production processes).
   - ○ A) Production department has its own way of representing information and it is always clear to us
   - ○ B) Production department has its own way of representing information and it is mostly clear to us
   - ○ C) Production department has its own way of representing information and it is somewhat clear to us
   - ○ D) Production department has its own way of representing information and it is unclear to us
2. Degree of understandingn of notation for example drawing conventions.
   - ○ A) Production department uses its own notation and it is always clear to us.
   - ○ B) Production department uses its own notation and it is mostly clear to us
   - ○ C) Production department uses its own notation and it is somewhat clear to us
   - ○ D) Production department uses its own notation and it is unclear to us
3. Degree of understanding of specific technical terms used.
   - ○ A) Production department uses its own terminology and it is always clear to
   - ○ B) Production department uses its own terminology and it is mostly clear to us
   - ○ C) Production department use its own terminology and it is somewhat clear to
   - ○ D) Production department uses its own terminology and it is unclear to us

**Availability of production system information**

4. How often information about the own company's production is distributed to product designer?
   - ○ A) Regularly and there is continuous effort to adjust the distribution process according to needs
   - ○ B) it is regular distributed to me
   - ○ C) If I ask for it
   - ○ D) Not necessary
5. How often information about production specifications is distributed todesigner?
   - ○ A) Regularly and there is continuous effort to adjust the distribution process according to needs
   - ○ B) it is regular distributed to me
   - ○ C) If I ask for it
   - ○ D) Not necessary

*Figure 10.19 – A screenshot of knowledge and information sharing evaluation*

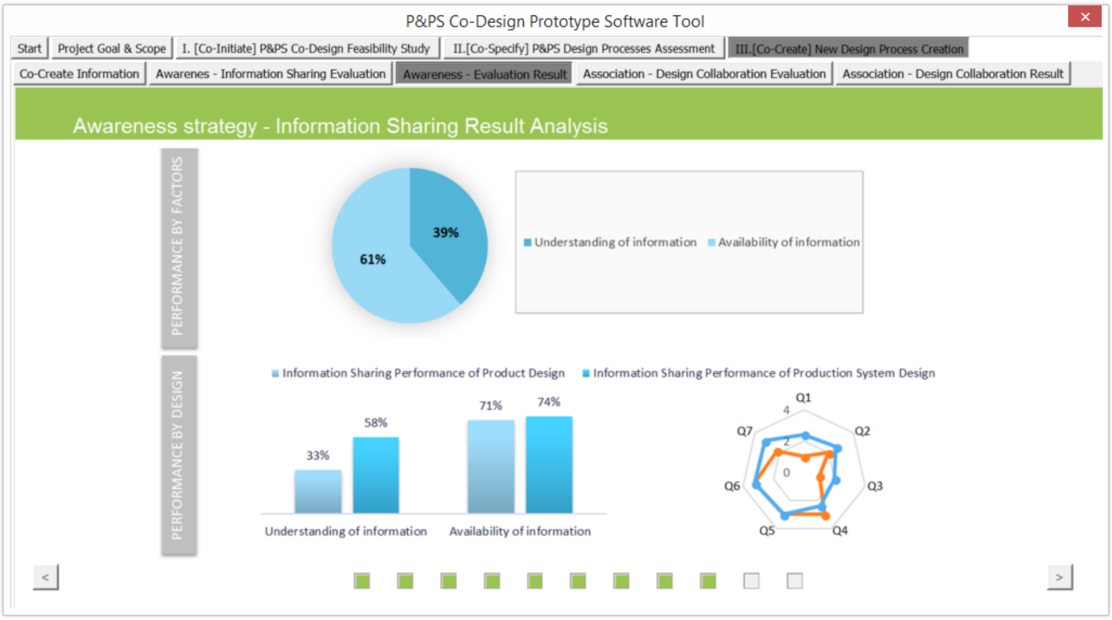
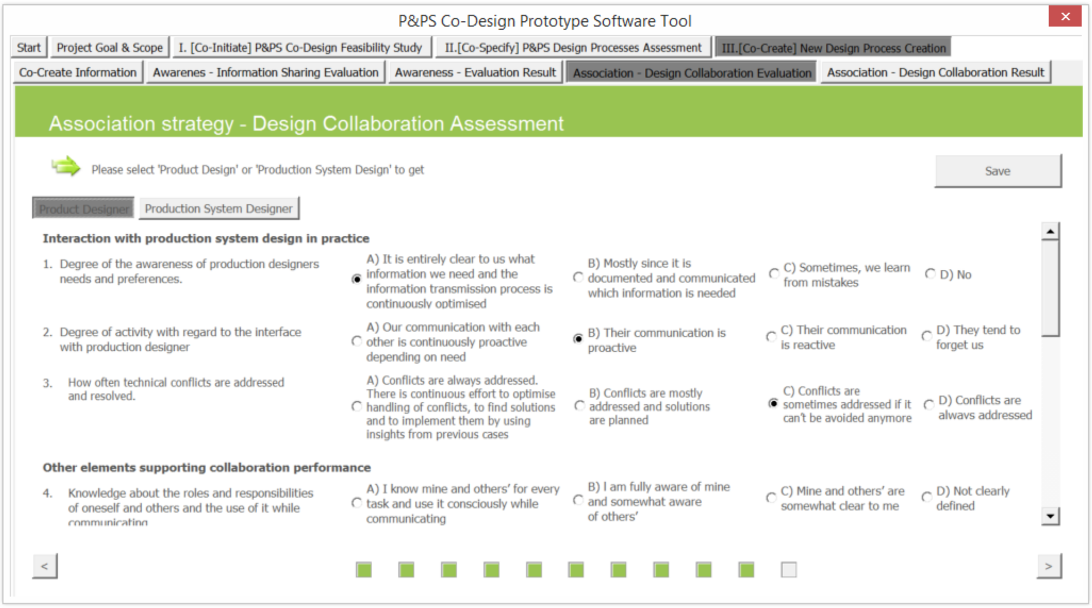


*Figure 10.20 – A screenshot of a result of knowledge and information sharing evaluation*

### *10.5.2 Association strategy*

Through the application of Association strategy, an improvement in design collaboration performance can be implemented using the ‘design collaboration checklists’ screen, as depicted in Figure 10.21. Similar to the information sharing evaluation, this screen collects the relevant design collaboration data from designers. The results of the analysis of the performance of design interaction and elements supporting collaboration are presented in ‘a result of design collaboration evaluation’ screen (see Figure 10.22).



Association strategy - Design Collaboration Assessment

Please select 'Product Design' or 'Production System Design' to get

**Interaction with production system design in practice**

| | | | | |
|---|---|---|---|---|
| 1. Degree of the awareness of production designers needs and preferences. | ● A) It is entirely clear to us what information we need and the information transmission process is continuously optimised | ○ B) Mostly since it is documented and communicated which information is needed | ○ C) Sometimes, we learn from mistakes | ○ D) No |
| 2. Degree of activity with regard to the interface with production designer | ○ A) Our communication with each other is continuously proactive depending on need | ● B) Their communication is proactive | ○ C) Their communication is reactive | ○ D) They tend to forget us |
| 3. How often technical conflicts are addressed and resolved. | ○ A) Conflicts are always addressed. There is continuous effort to optimise handling of conflicts, to find solutions and to implement them by using insights from previous cases | ○ B) Conflicts are mostly addressed and solutions are planned | ● C) Conflicts are sometimes addressed if it can't be avoided anymore | ○ D) Conflicts are always addressed |

**Other elements supporting collaboration performance**

| | | | | |
|---|---|---|---|---|
| 4. Knowledge about the roles and responsibilities of oneself and others and the use of it while communicating | ○ A) I know mine and others' for every task and use it consciously while communicating | ○ B) I am fully aware of mine and somewhat aware of others' | ○ C) Mine and others' are somewhat clear to me | ○ D) Not clearly defined |

Figure 10.21 – A screenshot of the design collaboration evaluation

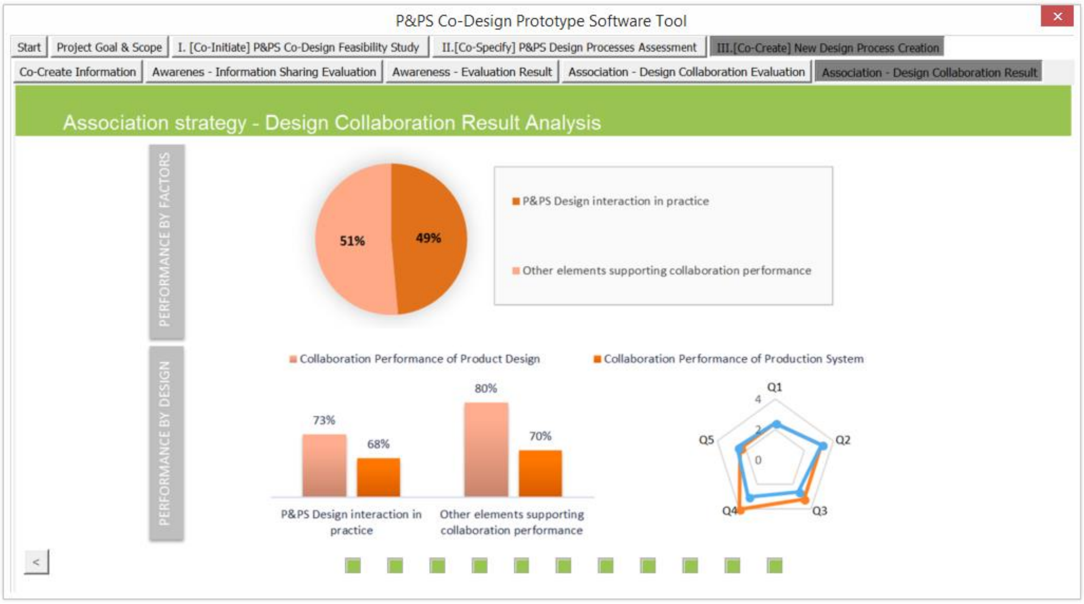


Figure 10.22 – A screenshot of a result of design collaboration evaluation

### *10.5.3 Adaptation strategy*

Through Adaptation strategy, the generation of a new combined P&PS co-design process can be accomplished. To achieve this, the research has utilised the Design Structure Matrix v1.6 tool to support the rearrangement of design activities through two main steps. First, all design activities and dependencies between these activities can be inputted in 'element' and 'dependencies' sheets, respectively, and, a 'DSM' sheet automatically illustrates interrelation between activities in the form of a black dot as shown in Figure 10.23. This tool then rearranges the inputted activities by selecting the 'Dependency sequence' function (see Figure 10.24). These activities are moved in order to reduce the distance between all black dots and a central line in which this represents the minimisation of the duration of information feedback loop for improving information transfer between design activities.

Importantly, before implementing a change to design process through this Adaptation strategy, a company must improve the existing information sharing/exchange or data management tools and establish closer design collaboration by using the set of tools outlined in Section 10.2.

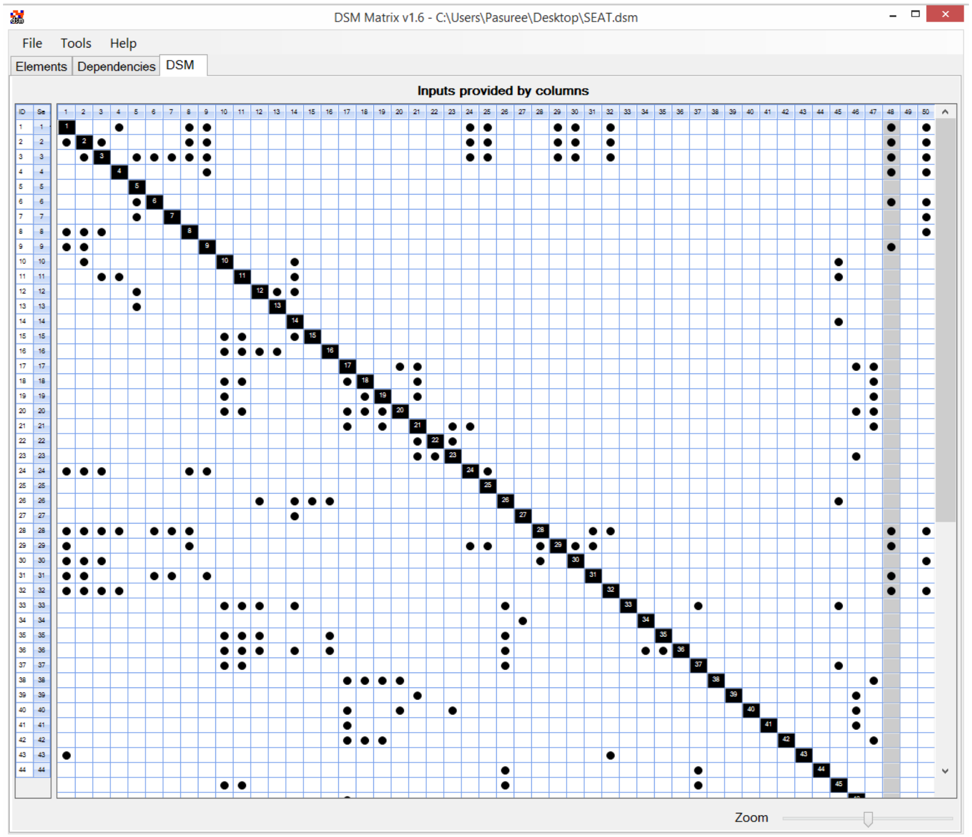
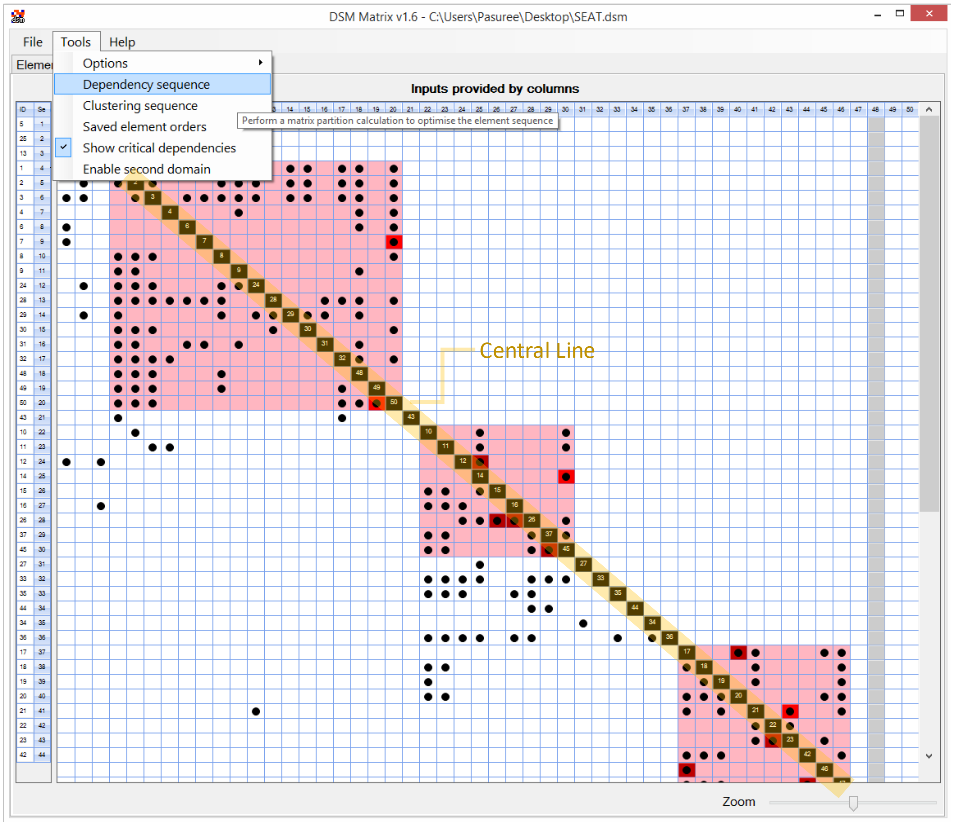


*Figure 10.23 – Design Structure Matrix v1.6 software tool from Project DSM Pty Ltd (Input)*



Perform a matrix partition calculation to optimise the element sequence

*Figure 10.24 – Design Structure Matrix v1.6 software tool from Project DSM Pty Ltd (Result)*

## 10.6 CHAPTER SUMMARY

This chapter has described an overview of the Co-implement phase as well as PPC software tool generated by this research to support the implementation of Co-initiate, Co-specify, and Co-create phase. To demonstrate and refine the application of P&PS framework, two case studies are used based on simple and complex product design and outlined in Chapter 11.

# CHAPTER 11 CASE STUDIES

## 11.1 INTRODUCTION

This chapter reports a summary of two case studies conducted to demonstrate the proposed framework for co-designing P&PS to improve resource efficiency. The two case studies are demonstrated through simple and complex product designs which have a dramatically high frequency of design updates and high resource consumption to present the applicability of the simple and complex design framework approaches. At the end of this chapter, the results of these case studies are discussed to summarise the effectiveness of the proposed P&PS Co-design framework.

## 11.2 CASE STUDIES FOR CO-DESIGNING P&PS TO SUPPORT RESOURCE-EFFICIENT MANUFACTURING

This research has proposed new approaches to identify the potential P&PS candidates for improving their design processes, to assess how their processes could be improved and collaborated, and to provide guidance for creating and implementing a P&PS Co-design process via the proposed framework. In order to refine these approaches, this framework was tested through two case studies to demonstrate the effectiveness of the framework and to improve the applicability and the advantage of the framework. For these purposes, the potential product designs which are feasible to co-design were explored. According to the explanation in the previous chapters, not every manufacturer will gain the potential benefit from the co-design implementation. Based on the proposed key criteria, two case studies were conducted using the suitable manufacturing companies which often update their product designs, frequently change the process facilities based on the product updates and have the intensive resource consumption.

For the first case study, a paper-based packaging industry was chosen because this has a high frequency of design update and high resource consumption during manufacturing and use phases. Even though a demand of paper consumption was expected to decline due to an entry of electronic data; in fact, it was reported that world consumption of paper and board had been dramatically increased approximately 533% in past 60 years (Finnish Forest Industries 2017). In 2006-2016, the level of paper consumption worldwide has reached about 400 million tonnes each year. Although the use of recycling paper can decrease a requirement of new material use, the energy and water consumption of paper production is considerably high to satisfy this excessive demand each year. Importantly, to reduce resource use and support current eco-design practices in paper and cardboard packaging industry, Koklacova and Atstaja (2011) have raised a need of collaboration between packaging designers and manufacturers to mitigate a lack of interdisciplinary knowledge about product design and the process of production.

For the second case study, automotive seat design and manufacturing industry was selected. In the context of automotive development, the automotive seat is considered as a high-frequency design update in comparison with its life expectancy. Much attention has been paid to automotive industry due to the high resource consumption during production and use phase as well as the pressure of environmental legislation in the past two decades. SMMT (2017) has reported that, in 2016, energy, material and water per vehicle production in the automotive company were reduced by 3.2%, 33.7%, and 3.5% respectively. However, there still is a need to further achieve an improvement of resource efficiency in the automotive supply chain, especially outside the EU.

These two case studies were not managed concurrently in which these started with the implementation of the packaging design case study. In detail, this began with collecting P&PS data and testing the simple design framework by packaging company. Therefore, the result and feedback from this case study were applied to improve and refine the applicability of approaches within the framework. Then, the refined framework approach was distributed to both of a packaging designer and an automotive seat design engineer for implementing these simple and complex design framework approaches.

More detail of these case studies is described in the two following sections. Each section includes the data collection and synthesis, the applications of Co-initiate, Co-specify and Co-create phase and the result and discussion of the case study.

## 11.3 CASE STUDY 1: PACKAGING DESIGN AND MANUFACTURING

The first case study was conducted in collaboration with an experienced packaging company X in Thailand. This company, which is a small and medium-sized enterprise, offers a wide range of customisable products including cosmetic packaging, food packaging, customised shopping bag, customised packaging label, and other printing products such as a customised folder, customised printing, book as depicted in Figure 11.1. These products are internally designed by central control and central design organisation and manufactured by an in-house production system.

### *11.3.1 Case Study Data*

The first group of data required for an application of Co-initiate phase includes product list, the frequency of product design update, product service life, and production system. The sources of this data are summarised in Table 11.1. Due to the data unavailability, the number of machines and working hours of production systems was assumed for applying a resource consumption assessment of production system. For the implementation of Co-specify and Co-create phase, data related to P&PS design processes and design decisions of P&PS are collected through email exchanges, telephone interviews and the completion of the provided checklists by a designer with 14 years of experience and a senior designer with 19 years of experience. At this step, there is a challenge in collecting data related design processes and its production system due to a lack of formal and structured design process in practice.

*Table 11.1 – Sources of data used in the case study 1*

| **Data Source** | **Data type** |
|---|---|
| A collaborated company | Product list<br>A frequency of product design update<br>Product life expectancy<br>Production process flow<br>Energy consumption<br>Design process data |
| Actual data | Energy consumption of each process<br>Material consumption of each process |
| Assumption | Working hour and number of machines of a production system |

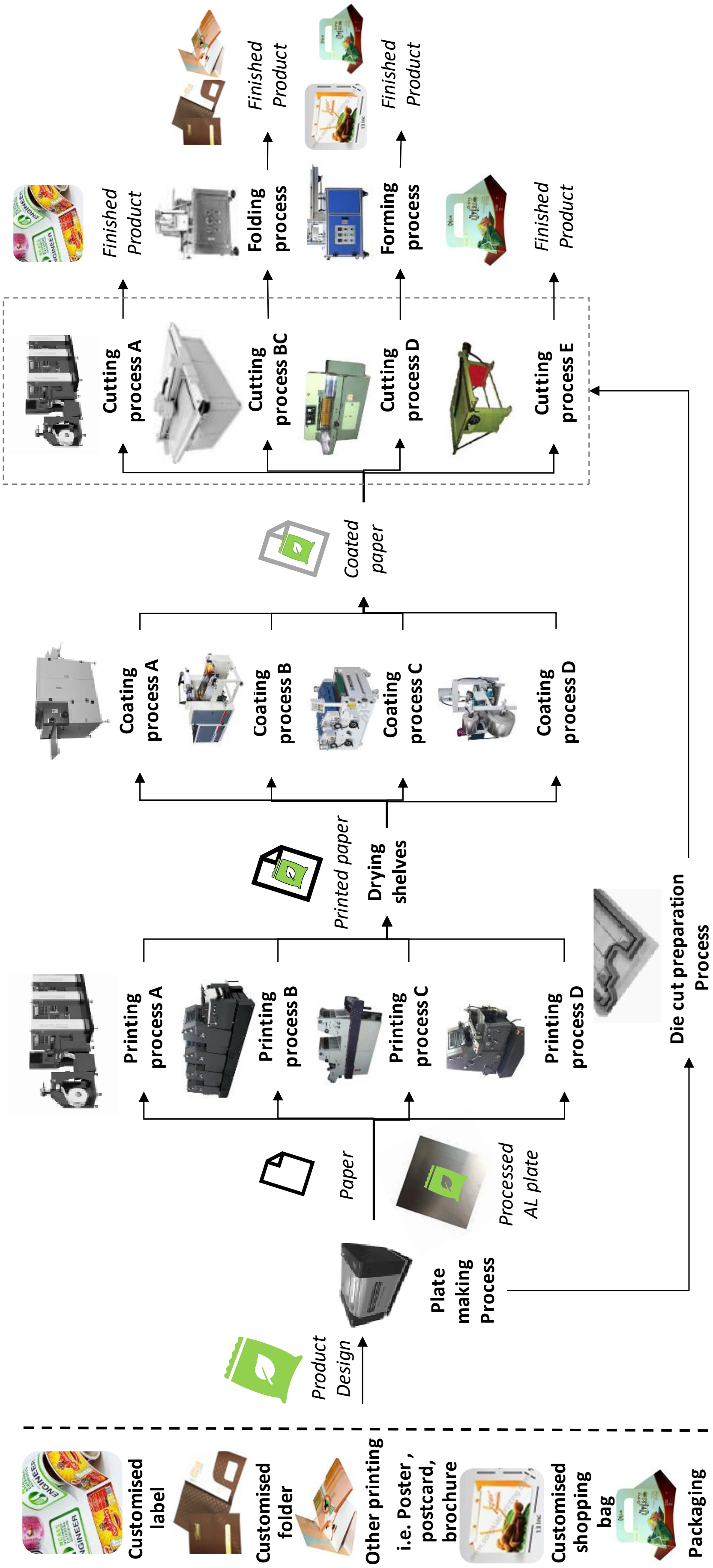


Figure 11.1 – Products and production system of a packaging company A

### *11.3.2 The Application of Co-Initiate Phase*

In this section, the feasibility of Co-design adoption was managed through:

i) Measuring the frequency of design update and interrelation between P&PS design update,

ii) Assessing resource consumption

iii) Identifying P&PS candidates for a co-design process as described in the following subsections.

#### *11.3.2.1 Measuring the frequency of design update and interrelation between P&PS design update between P&PS designs*

A data related to the frequency of product design update, product life expectancy and an effect between P&PS of seven main product types were collected as shown in Table 11.2. This table also presents the calculated results of the PDU value of each product. Based on the specified classification for Co-Design implementation in Table 8.1, the result reveals that the designs of a shopping bag, a customised folder, a customised printing and a customised book were suggested to design by the current design processes. This is because although the designs of these products were frequently updated, the change of their PSDs did not depend on the changes in PD (FPD ≠ FPS). Therefore, packaging, customised label and the other printing product that their design frequently updates and necessitate the changes of their PSDs (e.g. printing plate and die cutting tool) need to assess their resource consumptions further to identify the potential candidates for a co-design process.

*Table 11.2 – Data for identifying PDU and the interrelation between PD and PSD update*

| | **Product Type** | **Frequency of PD update** | **Product Lifespan** | **PDU** | **Frequency of PSD update** |
|---|---|---|---|---|---|
| 1 | Packaging e.g. cosmetic box, food packaging, crape box, food tray, dessert box, etc. | Daily | > 1 Year | 0.97 - 0.99 | Daily |
| 2 | Shopping bag | Daily | > 1 Year | 0.97 - 0.99 | No change |
| 3 | Customised folder | Monthly | > 1 Year | 0.917 | No change |
| 4 | Customised label e.g. product label, product tag, and sticker label | Daily | > 1 Year | 0.97 - 0.99 | Daily |
| 5 | Customised printing e.g. poster, postcasd, brochure | Every 2-3 months | > 1 Year | 0.75 - 0.83 | No change |
| 6 | 6.Book | - | > 1 Year | - | No change |
| 7 | Other printing e.g. Air Freshener, Room tag, | Daily | > 1 Year | 0.97 - 0.99 | Daily |

#### *11.3.2.2 Assessing the resource consumption of a packaging production system*

In this section, the production system of the three identified product designs was assessed for their resource consumption. This production system consists of 14 production processes for printing plate preparation, die cutting preparation, printing, drying, cutting, folding and forming processes as shown in the production process flow (see Figure 11.2). Based on the data of process output and the assumption of the working hour (8 hours per day, 5 days per week and 50 weeks per year), the input materials of each machine were simulated via the material flow assessment using the STAN2.6 software tool. The detail data of resource consumption assessment is provided in Appendix III.

As the results, the material efficiency of the entire production system was not highly critical since the material waste was determined as 11.68% of total input material. Nevertheless, in a context of material weight, this production system wasted 1,975.2 tons of materials per year. Most of these wastes (63.27% of all material wastes) were produced from the cutting processes. Based on the assumed allowance of waste efficiency at 20%, the cutting machine A, BC, D and E were denoted as the material hotspots with waste generation at 24.02%, 23.27% ,25% and 32% respectively (see Figure 11.3). In addition, the block screen process has dramatically high reject rate at 100%. This is because, for every new design, this process has to produce a new printing plate and a new die cutting for printing and cutting process while the existing ones are discarded. However, this process wasted only 0.03% of all material waste (see Figure 11.4).

Apart from these processes, it is suggested to start monitoring the material efficiency of coating machine B because the waste efficiency (19.91%) almost exceeds the maximum limit. In a context of energy consumption, the printing machine A, B and C were considered as the energy hotspot because their energy efficiencies which are at 62.5% 54.42% and 62.5%, respectively were lower than the minimum limit (at 70%) as shown in Figure 11.5.

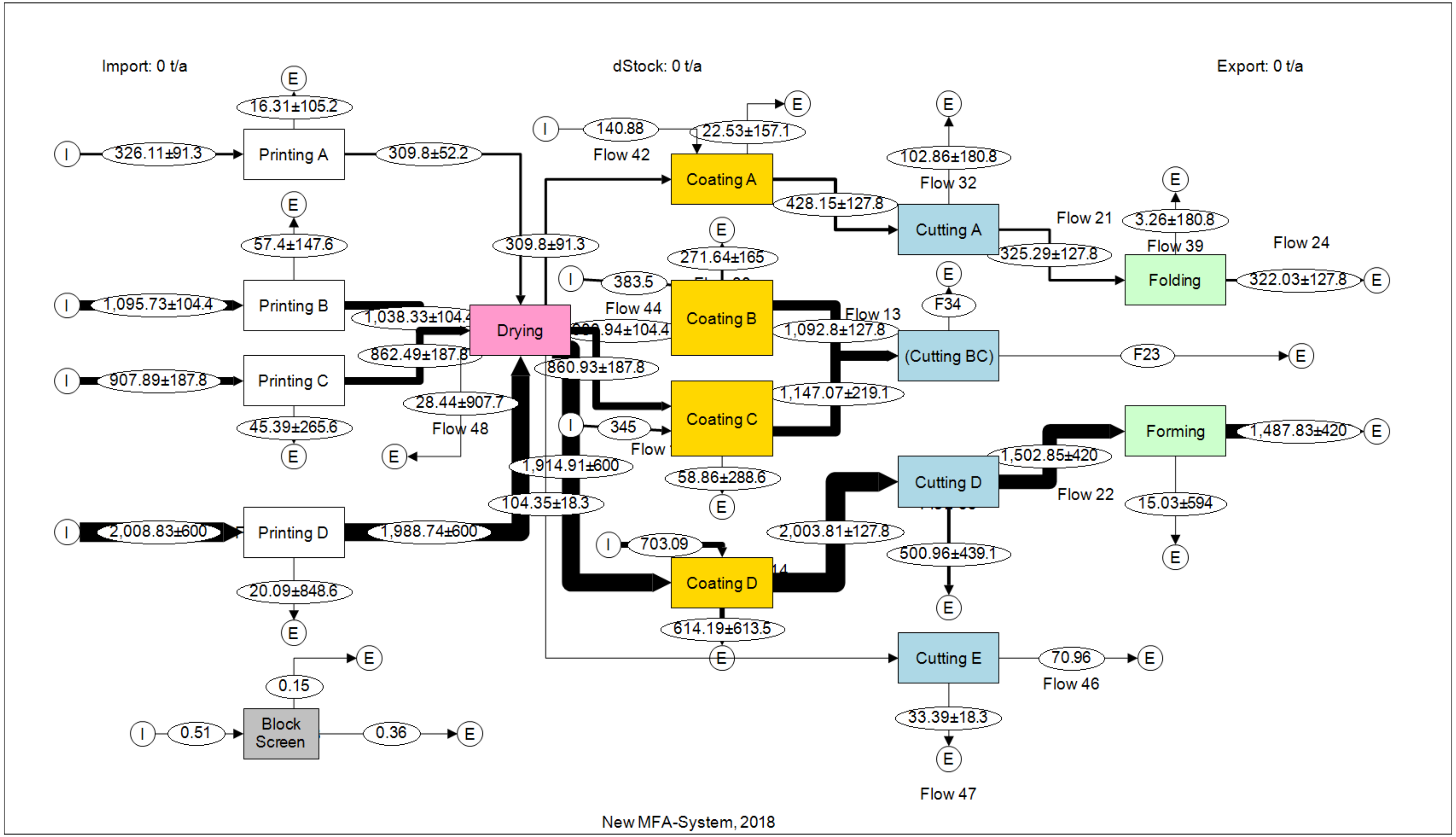


*Figure 11.2 – Material flow assessment using the STAN2.6 software tool*

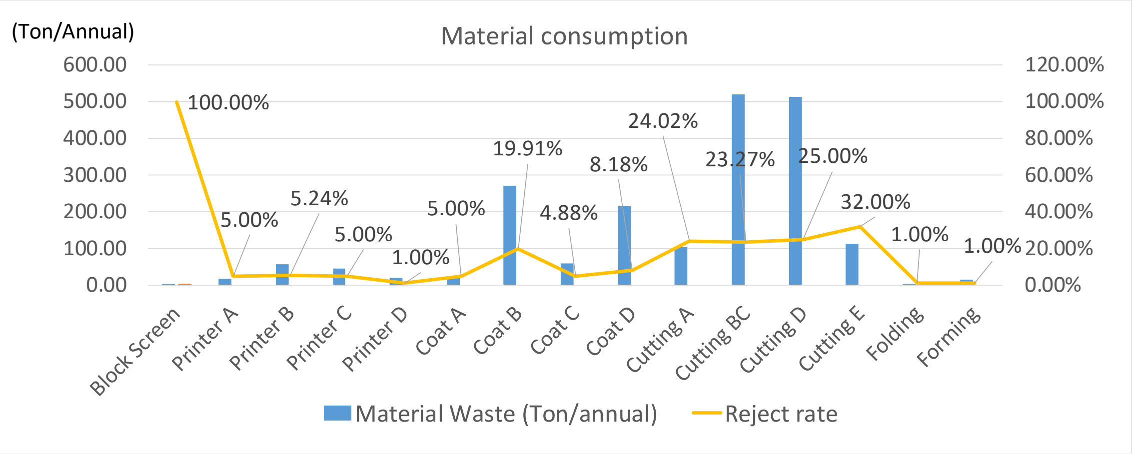


*Figure 11.3 – Result of material consumption assessment (by the process)*

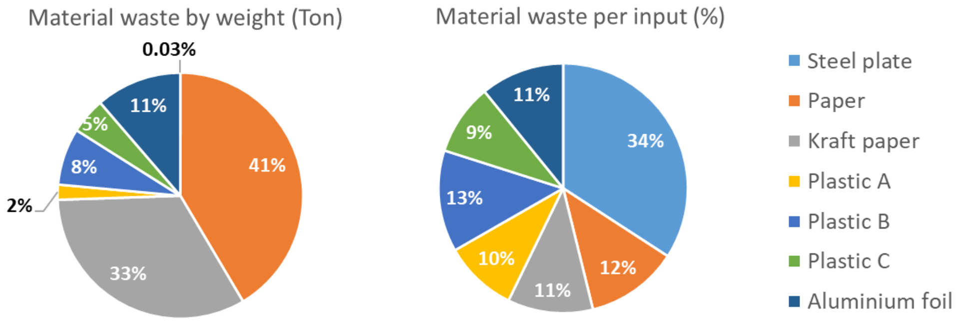
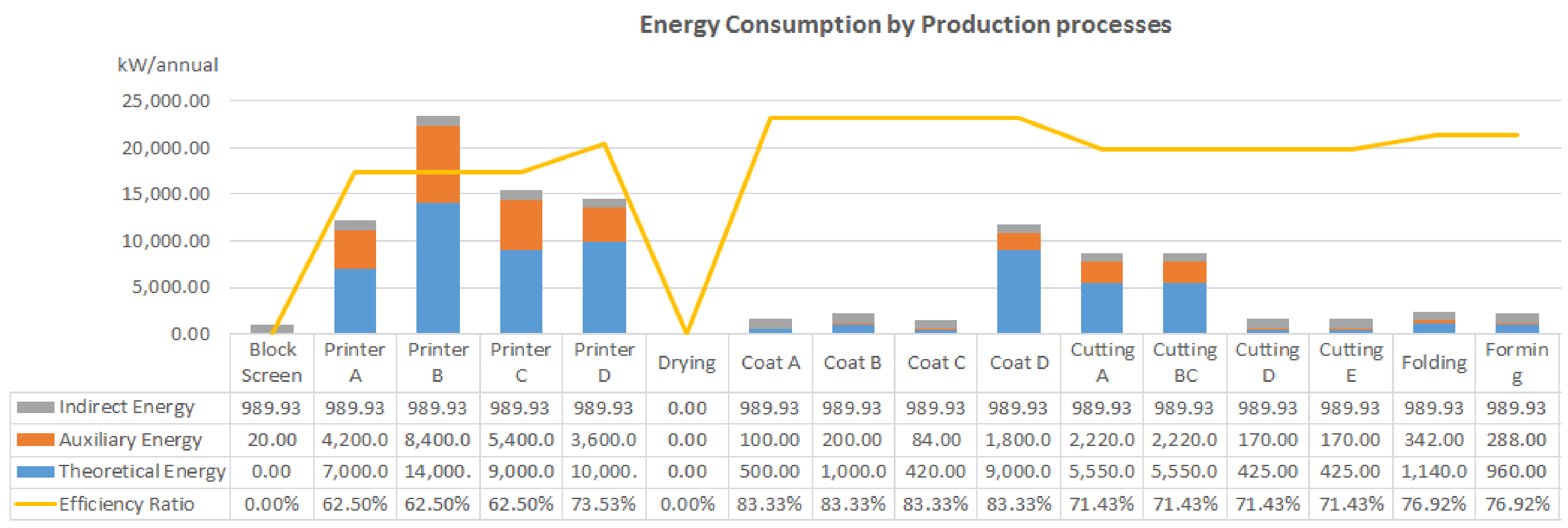


*Figure 11.4 – Result of material consumption assessment (by material)*

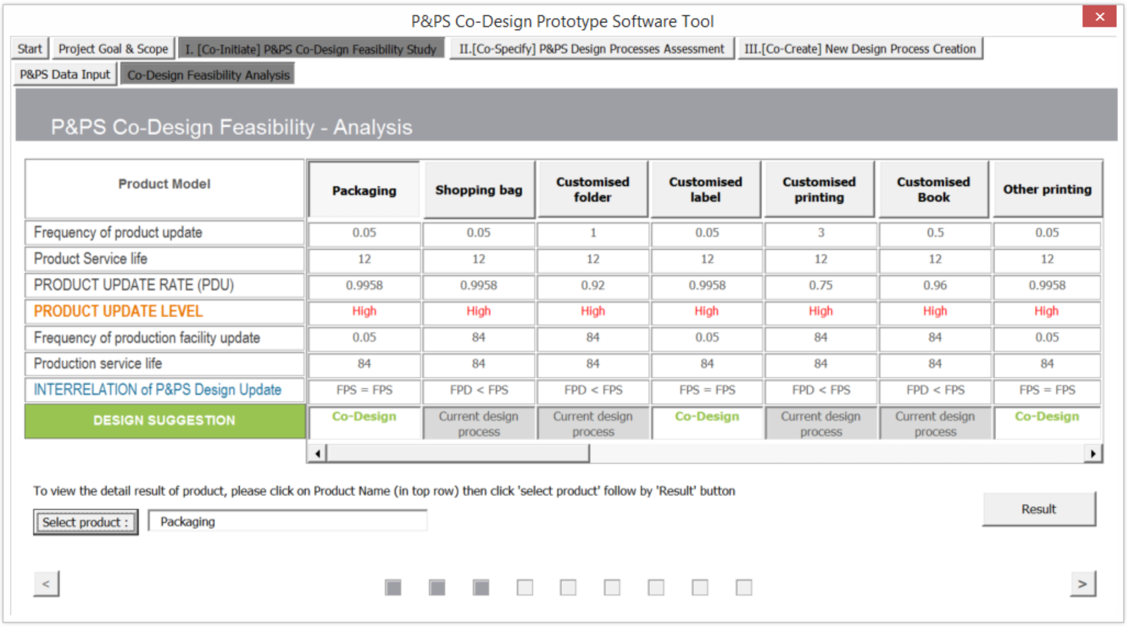
### *11.3.2.3 Identifying P&PS candidates for a co-design process*

Based on the classification criteria in Table 8.1, this company was suggested to adopt a new single co-design process for designing three candidates which are packaging, customised label and other printing products (see Figure 11.6). As the results, these three product designs had a high frequency of product update ($0.97 \leq PDU \leq 0.99$), an interdependency between design updates of P&PS and the high material and energy consumptions. The production process hotspots of these three product designs are the cutting machine A, BC, D and E as well as the printing machine A, B and C.



| | Block Screen | Printer A | Printer B | Printer C | Printer D | Drying | Coat A | Coat B | Coat C | Coat D | Cutting A | Cutting BC | Cutting D | Cutting E | Folding | Formin g |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ▆ Indirect Energy | 989.93 | 989.93 | 989.93 | 989.93 | 989.93 | 0.00 | 989.93 | 989.93 | 989.93 | 989.93 | 989.93 | 989.93 | 989.93 | 989.93 | 989.93 | 989.93 |
| ▆ Auxiliary Energy | 20.00 | 4,200.0 | 8,400.0 | 5,400.0 | 3,600.0 | 0.00 | 100.00 | 200.00 | 84.00 | 1,800.0 | 2,220.0 | 2,220.0 | 170.00 | 170.00 | 342.00 | 288.00 |
| ▆ Theoretical Energy | 0.00 | 7,000.0 | 14,000. | 9,000.0 | 10,000. | 0.00 | 500.00 | 1,000.0 | 420.00 | 9,000.0 | 5,550.0 | 5,550.0 | 425.00 | 425.00 | 1,140.0 | 960.00 |
| — Efficiency Ratio | 0.00% | 62.50% | 62.50% | 62.50% | 73.53% | 0.00% | 83.33% | 83.33% | 83.33% | 83.33% | 71.43% | 71.43% | 71.43% | 71.43% | 76.92% | 76.92% |

*Figure 11.5 – Result of energy consumption of each production processes*



| Product Model | Packaging | Shopping bag | Customised folder | Customised label | Customised printing | Customised Book | Other printing |
|---|---|---|---|---|---|---|---|
| Frequency of product update | 0.05 | 0.05 | 1 | 0.05 | 3 | 0.5 | 0.05 |
| Product Service life | 12 | 12 | 12 | 12 | 12 | 12 | 12 |
| PRODUCT UPDATE RATE (PDU) | 0.9958 | 0.9958 | 0.92 | 0.9958 | 0.75 | 0.96 | 0.9958 |
| PRODUCT UPDATE LEVEL | High | High | High | High | High | High | High |
| Frequency of production facility update | 0.05 | 84 | 84 | 0.05 | 84 | 84 | 0.05 |
| Production service life | 84 | 84 | 84 | 84 | 84 | 84 | 84 |
| INTERRELATION of P&PS Design Update | FPS = FPS | FPD < FPS | FPD < FPS | FPS = FPS | FPD < FPS | FPD < FPS | FPS = FPS |
| DESIGN SUGGESTION | Co-Design | Current design process | Current design process | Co-Design | Current design process | Current design process | Co-Design |

To view the detail result of product, please click on Product Name (in top row) then click 'select product' follow by 'Result' button

Select product : Packaging

*Figure 11.6 - P&PS candidates for a co-design process*

### *11.3.3 The Application of Co-Specify Phase*

At this phase, P&PS design processes were assessed and analysed to identify which design decisions requires co-design consideration to reduce resource consumption of the identified hotspots within this packaging company. Thus, the simple design framework approach which involves the below steps was applied, and the result is described in the following subsections:

i. Identification of ecological design decision,

ii. An assessment of interrelation between P&PS design decisions.

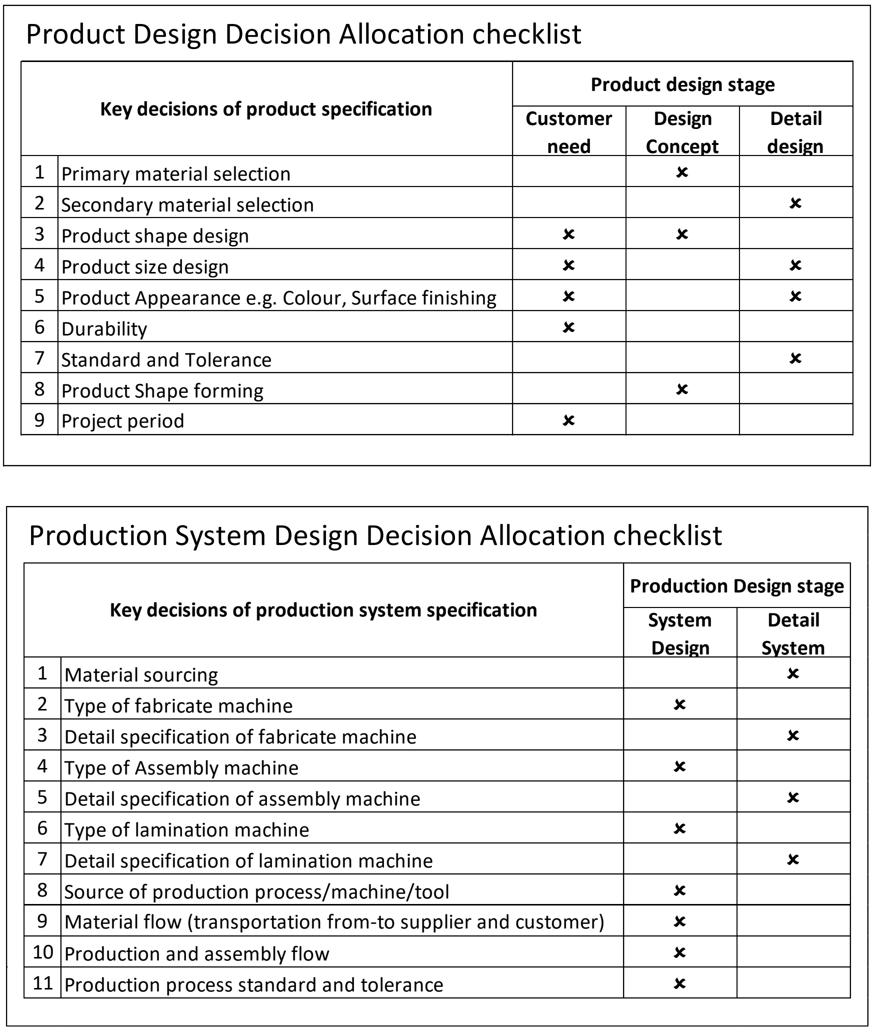
iii. A recommendation of the most suitable co-create strategy.

#### *11.3.3.1 Identification of ecological design decision*

At this step, design decisions within the P&PS design processes used by company X are identified when they are decided within design processes and assessed their impacts on resource consumption. These were completed through two sub-steps respectively.

First, the developed design specification allocation checklists have been filled by a packaging designer. In this application, there was a difficulty in utilising this set of checklists because this company has designed all ranges of their products and their production system by using the similar informal design steps and a designer was also lack of knowledge related to a formal design process. To realise the actual design processes, the allocation of design decisions has been completed based on the information provided in the filled check sheets and the numbers of the interviews with two designers and presented in Figure 11.7.

For the second step, these design decisions were assessed for their impact on resource consumption and resource efficiency improvement. Based on the results of resource consumption assessment, the criteria used for this eco-classification was identified and shown in Appendix C. Then, the ecological identification checklists (see Figure 11.8) were completed by a designer. As a result, only one product design decision (project period) and four production system design decisions (material sourcing, detail specification of the assembly process, detail specification of lamination process and material flow) were determined to have no impact on resource efficiency improvement. Therefore, these decisions were not considered and included in the P&PS design interrelation assessment.



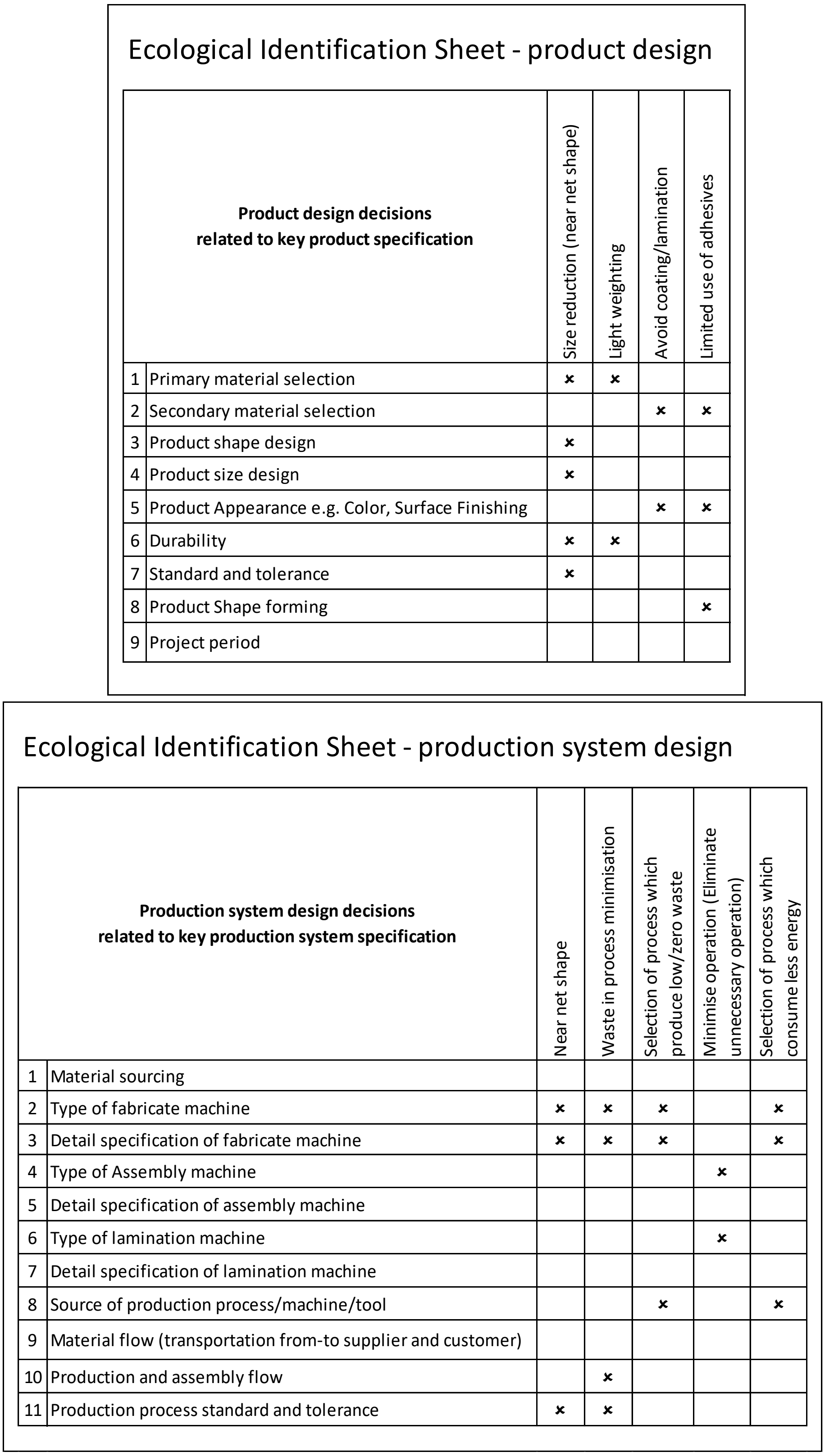
Product Design Decision Allocation checklist

| Key decisions of product specification | | Product design stage | | |
|---|---|---|---|---|
| | | Customer need | Design Concept | Detail design |
| 1 | Primary material selection | | × | |
| 2 | Secondary material selection | | | × |
| 3 | Product shape design | × | × | |
| 4 | Product size design | × | | × |
| 5 | Product Appearance e.g. Colour, Surface finishing | × | | × |
| 6 | Durability | × | | |
| 7 | Standard and Tolerance | | | × |
| 8 | Product Shape forming | | × | |
| 9 | Project period | × | | |

Production System Design Decision Allocation checklist

| Key decisions of production system specification | | Production Design stage | |
|---|---|---|---|
| | | System Design | Detail System |
| 1 | Material sourcing | | × |
| 2 | Type of fabricate machine | × | |
| 3 | Detail specification of fabricate machine | | × |
| 4 | Type of Assembly machine | × | |
| 5 | Detail specification of assembly machine | | × |
| 6 | Type of lamination machine | × | |
| 7 | Detail specification of lamination machine | | × |
| 8 | Source of production process/machine/tool | × | |
| 9 | Material flow (transportation from-to supplier and customer) | × | |
| 10 | Production and assembly flow | × | |
| 11 | Production process standard and tolerance | × | |

*Figure 11.7 – A result of P&PS design decision allocation*



Ecological Identification Sheet - product design

| | **Product design decisions related to key product specification** | Size reduction (near net shape) | Light weighting | Avoid coating/lamination | Limited use of adhesives |
|---|---|---|---|---|---|
| 1 | Primary material selection | × | × | | |
| 2 | Secondary material selection | | | × | × |
| 3 | Product shape design | × | | | |
| 4 | Product size design | × | | | |
| 5 | Product Appearance e.g. Color, Surface Finishing | | | × | × |
| 6 | Durability | × | × | | |
| 7 | Standard and tolerance | × | | | |
| 8 | Product Shape forming | | | | × |
| 9 | Project period | | | | |

Ecological Identification Sheet - production system design

| | **Production system design decisions related to key production system specification** | Near net shape | Waste in process minimisation | Selection of process which produce low/zero waste | Minimise operation (Eliminate unnecessary operation) | Selection of process which consume less energy |
|---|---|---|---|---|---|---|
| 1 | Material sourcing | | | | | |
| 2 | Type of fabricate machine | × | × | × | | × |
| 3 | Detail specification of fabricate machine | × | × | × | | × |
| 4 | Type of Assembly machine | | | | × | |
| 5 | Detail specification of assembly machine | | | | | |
| 6 | Type of lamination machine | | | | × | |
| 7 | Detail specification of lamination machine | | | | | |
| 8 | Source of production process/machine/tool | | | × | | × |
| 9 | Material flow (transportation from-to supplier and customer) | | | | | |
| 10 | Production and assembly flow | | × | | | |
| 11 | Production process standard and tolerance | × | × | | | |

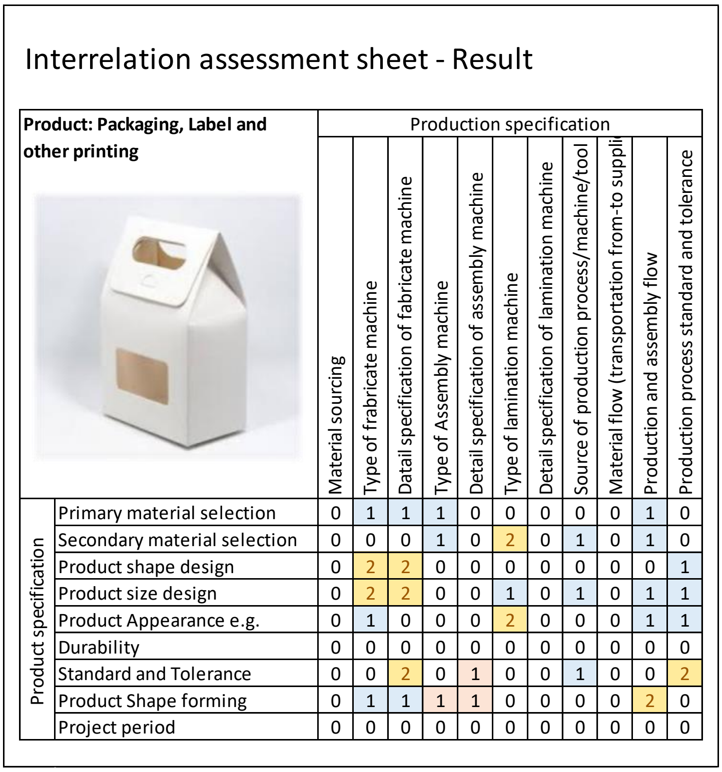
*Figure 11.8 – Ecological identification of PD and PSD decisions*

### *11.3.3.2 P&PS design interrelation assessment*

The design interrelation assessment checklists were prepared and determined by a packaging designer, and these are presented in Appendix III. Based on these filled PD and PSD checklists, the calculated result of the mapping is presented in Figure 11.9. As a result, it was found that 7 out of 9 (or 78%) of PD decisions were specified as the co-design specifications. Only the decisions related to product durability and project period were identified to have no potentially affect resource consumption. Moreover, 8 out of 11 (or 72%) of PSD decisions were also defined as the co-design specifications. The decision related to the setting of production process standard and tolerance was excluded in the co-design consideration.

### *11.3.3.3 a recommendation of the most suitable co-create strategy*

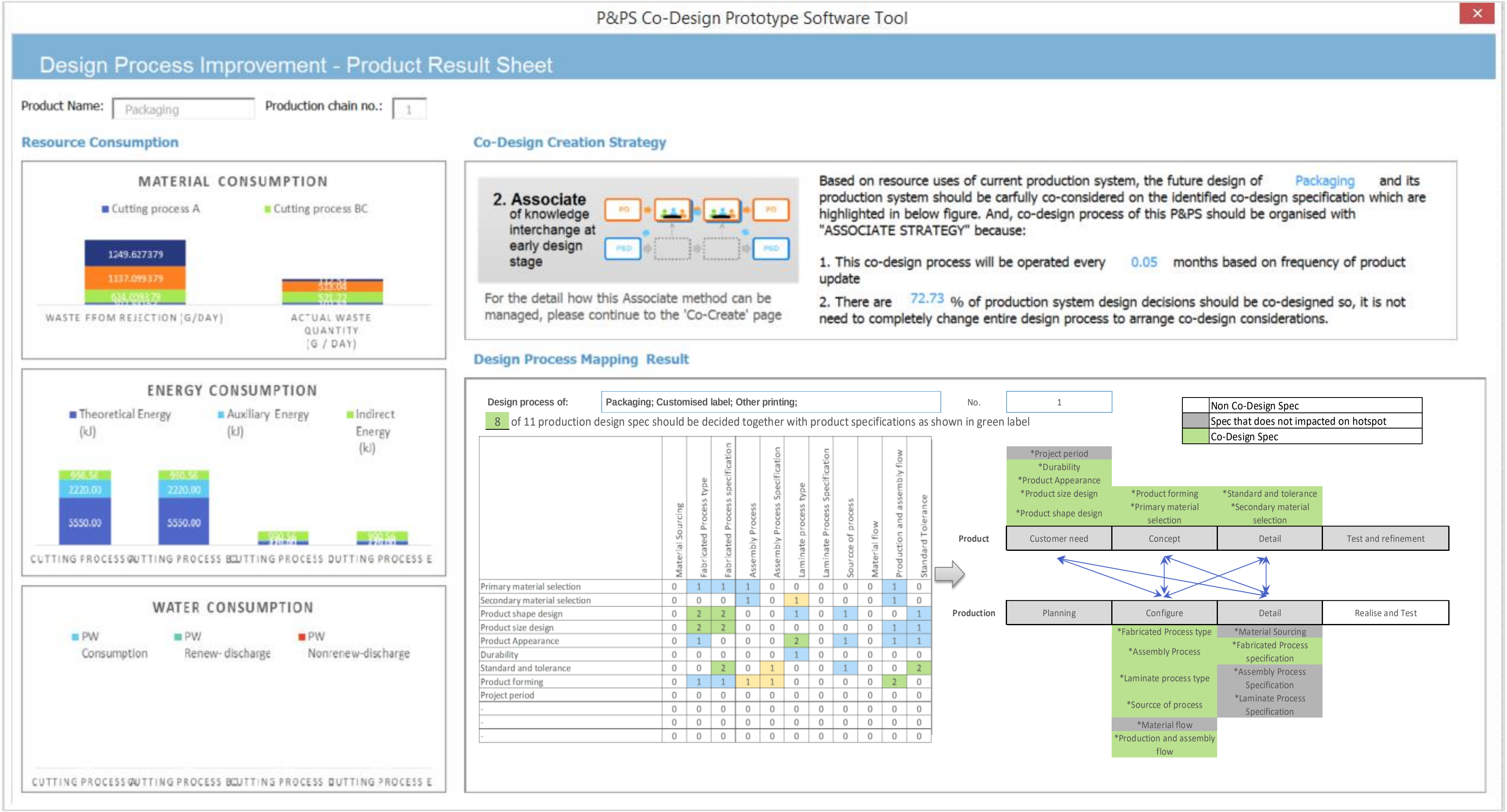
As a result of the interrelation assessment and the criteria suggested in Chapter 9, this company X is suggested to create and implement a new single process for co-designing packaging, customised label, other printing product and their production system by using the Association strategy since 72% of production system design decisions was advised to consider collaboratively with product decision within the simple design process (see Figure 11.10 and Appendix III).



Interrelation assessment sheet - Result

| **Product: Packaging, Label and other printing** | | Production specification | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Material sourcing | Type of frabricate machine | Datail specification of fabricate machine | Type of Assembly machine | Detail specification of assembly machine | Type of lamination machine | Detail specification of lamination machine | Source of production process/machine/tool | Material flow (transportation from-to suppli | Production and assembly flow | Production process standard and tolerance |
| Product specification | Primary material selection | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 0 |
| | Secondary material selection | 0 | 0 | 0 | 1 | 0 | 2 | 0 | 1 | 0 | 1 | 0 |
| | Product shape design | 0 | 2 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| | Product size design | 0 | 2 | 2 | 0 | 0 | 1 | 0 | 1 | 0 | 1 | 1 |
| | Product Appearance e.g. | 0 | 1 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 1 | 1 |
| | Durability | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Standard and Tolerance | 0 | 0 | 2 | 0 | 1 | 0 | 0 | 1 | 0 | 0 | 2 |
| | Product Shape forming | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 2 | 0 |
| | Project period | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

*Figure 11.9 – Design interrelation assessment between PD and PSD*



P&PS Co-Design Prototype Software Tool

## Design Process Improvement - Product Result Sheet

Product Name: Packaging  Production chain no.: 1

**Resource Consumption**

**Co-Design Creation Strategy**

**2. Associate** of knowledge interchange at early design stage

For the detail how this Associate method can be managed, please continue to the 'Co-Create' page

Based on resource uses of current production system, the future design of Packaging and its production system should be carfully co-considered on the identified co-design specification which are highlighted in below figure. And, co-design process of this P&PS should be organised with "ASSOCIATE STRATEGY" because:

1. This co-design process will be operated every 0.05 months based on frequency of product update

2. There are 72.73 % of production system design decisions should be co-designed so, it is not need to completely change entire design process to arrange co-design considerations.

**Design Process Mapping Result**

Design process of: Packaging; Customised label; Other printing;  No. 1

8 of 11 production design spec should be decided together with product specifications as shown in green label

| | Material Sourcing | Fabricated Process type | Fabricated Process specification | Assembly Process | Assembly Process Specification | Laminate process type | Laminate Process Specification | Sourcce of process | Material flow | Production and assembly flow | Standard Tolerance |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Primary material selection | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 0 |
| Secondary material selection | 0 | 0 | 0 | 1 | 0 | 1 | 0 | 0 | 0 | 1 | 0 |
| Product shape design | 0 | 2 | 2 | 0 | 0 | 1 | 0 | 1 | 0 | 0 | 1 |
| Product size design | 0 | 2 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 |
| Product Appearance | 0 | 1 | 0 | 0 | 0 | 2 | 0 | 1 | 0 | 1 | 1 |
| Durability | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 |
| Standard and tolerance | 0 | 0 | 2 | 0 | 1 | 0 | 0 | 1 | 0 | 0 | 2 |
| Product forming | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 2 | 0 |
| Project period | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| - | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| - | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| - | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

| | |
|---|---|
| ☐ | Non Co-Design Spec |
| ▨ | Spec that does not impacted on hotspot |
| 🟩 | Co-Design Spec |

*Figure 11.10 – Recommendation of the most suitable co-create strategy*

### *11.3.4 The Application of Co-Create Phase*

Through Association strategy, this company X was advised to implement i) the improvement of knowledge and information interchange and ii) strengthening design collaboration as follows.

At the former step, based on the current practice, this company was recommended to provide the knowledge related to a formal and structural product and production system design process for product and production system designer respectively. Then, the designers could be reskilled to understand overall P&PS design, sustainability, and resource efficiency. Moreover, to support co-design decisions, the information related to the identified production design decisions which are a type and specification of fabricated and assembly process, type of lamination process, the source of the production processes, a process flow and a process standard and tolerance could be documented, updated, and available to product designers. In the same way, the information related to the identified product design decisions is required to distribute to the production system designers.

At the latter step, design collaboration practice between product designers and production system designers could be evaluated, improved and practised at ‘collaboration level’ (see section 9.4.1). Significantly, after the improvement of knowledge and information interchange as well as design collaboration, the formal P&PS co-design processes need to be created, documented and distributed to all relevant designers to enable co-design consideration in this central design and central control practice.

With these new processes, a team of the assigned P&PS designers could consider minimisation of material waste from cutting processes and improve the energy efficiency of the printing processes by using the recommended resource efficiency strategies and considering options of the specified co-design decisions during consumer need identification, conceptual design and detail design steps.

### *11.3.5 Result and discussion of case study 1*

The implementation of the simple design framework approach has identified the need to improve the design activities of this packaging company X to achieve a resource-efficient production system. As the result of Co-initiate phase, the three product types (customised packaging, customised label and other printing) were considered to gain the potential benefit from a co-design process. This is because their product design and production facilities had a relatively high design update (due to daily design update) and a need to reduce resource use in a production system. Their production systems have produced a large number of material wastes, especially from cutting processes (63.27% of all material wastes) and consumed high energy in printing processes. Then, as the result of Co-specify phase, 9 resource efficiency strategies were suggested to apply by considering 7 PD and 8 PSD decisions concurrently to reduce the targeted hotspot processes. For example, PD decisions, which are the selection of primary materials and product durability, and PSD decisions, which are type and specification of fabricating process, type of assembly process and production process flow, are considered to identify the P&PS options based on light-weighting consideration. To realise the new co-design processes, company X was advised to apply Association strategy since most of PSD considerations need to consider together with PD decisions. Thus, it was recommended to reskill designers who require the ability to understand sustainability, resource efficiency and P&PS information for implementing a co-design process.

Moreover, based on nature of design practice in company X which product designers commonly predominant all design decisions, the design collaboration between product and production system designers needs to be improved carefully, and the information related to these identified design specifications should be documented, updated, and made available to support co-design decisions. Nevertheless, based on the nature of the product which highly depended on customer need, company X could also provide sustainability and resource efficiency knowledge and suggestion to their customer to achieve the improvement of resource efficiency.

## 11.4 CASE STUDY 2: AUTOMOTIVE SEAT DESIGN AND MANUFACTURING

The second case study was conducted by the collaboration with the experienced automotive seat design engineers. Nevertheless, due to the sensitivity of data and the confidential nature of information, the first part of this case study was tested based on the generated automotive seat production system. In assumption, a set of five automotive seat designs is generally designed by an automotive company A which is a large enterprise and has distributed control and distributed design organisation in collaboration with an automotive seat company B which offers design and manufacture service. The company B has three main type of production lines which are able to produce a seat head restraint, assemble the finished front seat and assemble the finished rear seat by using the supplied seat parts and components from five different production lines: seat frames, seat pad foams, plastic components, seat trim covering and leather productions.

### *11.4.1 Case study data*

The input data for the Co-design feasibility study was from three different sources. For determining PDU and an effect between PD and PSD, the frequency of seat design update and the frequency of seat production change were provided by interviews with the three experienced seat design engineers. Seat life expectancy was based on a life expectancy of a vehicle (SMMT 2017). For the resource consumption assessment, an input data related to the seat structure, components, materials and component weight were provided by Steinwall and Viippola (2014). Seat production system, production processes and production process flow were from two publications: Tsou and Chen (2005) and Manoj Bhalwankar and Sachin Mastud (2014). For the demonstration of Co-specify and Co-create phase, the information related design processes, design decisions and design organisation of P&PS were collected through telephone interview with two seat design engineers (with 5 and 6 years of experience) and the completion of the developed check sheets by an engineering design manager with 17 years' experience. All types of input data gathered from both primary and secondary sources were summarised in Table 11.3.

*Table 11.3 – Source of data used in the Case study 2*

| **Data Source** | **Data type** |
|---|---|
| Collaborated designers | A frequency of seat design update<br>Design process (include design decision and design organisation) |
| Literature | Automotive seat life expectancy<br>Seat part and seat structure<br>Seat production processes flow<br>Energy consumption of each process<br>Material consumption of each process |
| Assumption | Product list<br>Working hour of the production system<br>The fraction of material waste per material input |

### *11.4.2 The Application of Co-Initiate Phase*

At this first Co-initiate phase, the implementation of the Co-design feasibility study was processed following the steps explained in Figure 8.7.

#### *11.4.2.1 Measuring the frequency of design update and interrelation between P&PS design update between P&PS designs*

Based on the interview, all designs of automotive seat generally change following vehicle design change which is categorised into minor changes (every 24 months) and full model change (every 60 months). Based on a vehicle service life, seat life expectancy is 14 years (168 months) (SMMT, 2017). Therefore, the result of PDU is 0.86 and 0.64 for a minor change and full model change, respectively. For the interrelation between PD and PSD update, PSD commonly changes during a full model change and barely change during a minor change. In addition, PSD changes during full model change involve a new design of the trim cover, pad foam and frame. This also includes the selection of seat supplier and seat part suppliers. Thus, the production system of all five seats needs to assess the resource consumption to identify a candidate for a co-design process.

#### *11.4.2.2 Assessing the resource consumption of seat production system*

To assess the resource consumption, the production system of the automotive seat is assumed to process 8 hours per day, 6 days per week and 50 weeks per year. Based on this assumption, the resource consumption assessment of this seat production system was determined based on a seat production process flow in Figure 11.11. As a result, the material efficiency of this production system was not highly critical because only 7.87% of the total input is waste. This system nevertheless wasted 1,073,924 tons per year. The majority of this waste (29.77%) were from the cutting processes for leather and fabric trim cover which were denoted as material hotspots with waste generation at 33.63% and 23.30% respectively (see Figure 11.12). Also, although the seat frame production process has wasted only 10.83% of all input steel, this 408,424 tons of steel waste was considered as 50% of all material wastes (see Figure 11.14). In a context of energy consumption (see Figure 11.13), a stamping process of frame components, frame coating processes and three hot-injection processes of a seat pad foam were denoted as the energy hotspots of this production chain. Because their energy efficiencies which are at 58.39%, 59.52%, 59.26%, 59.26% and 59.26%, respectively, were lower than the minimum limit (at 60%).

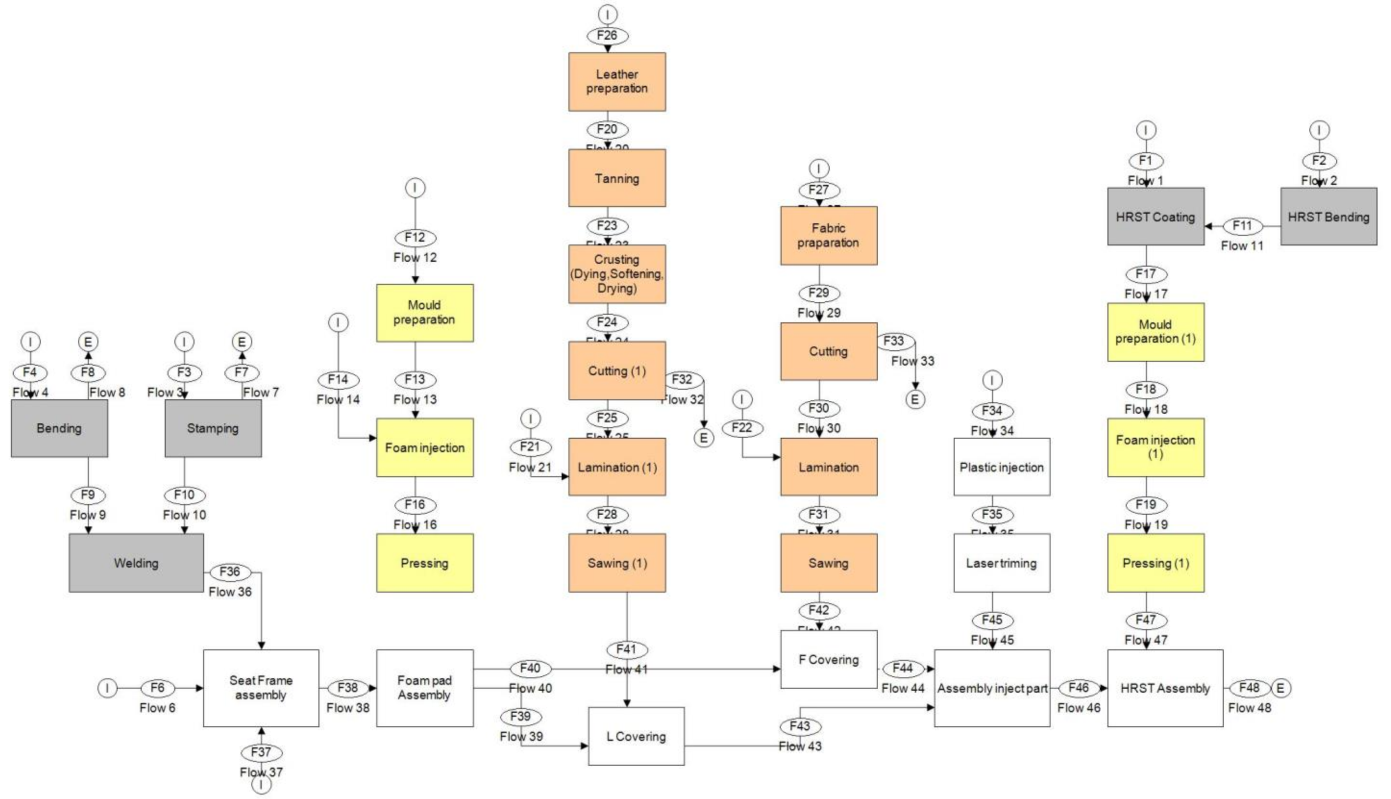


Figure 11.11 – Material flow assessment using the STAN2.6 software tool

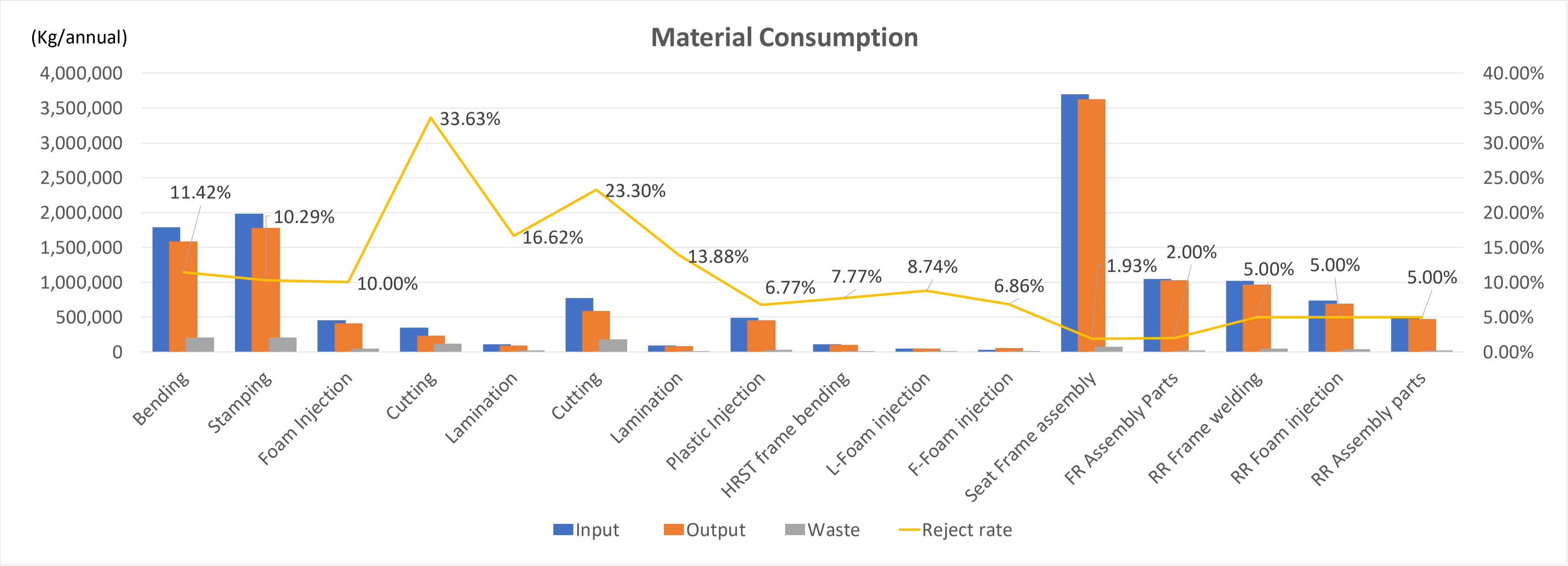


*Figure 11.12 – Result of material consumption assessment (by the process)*

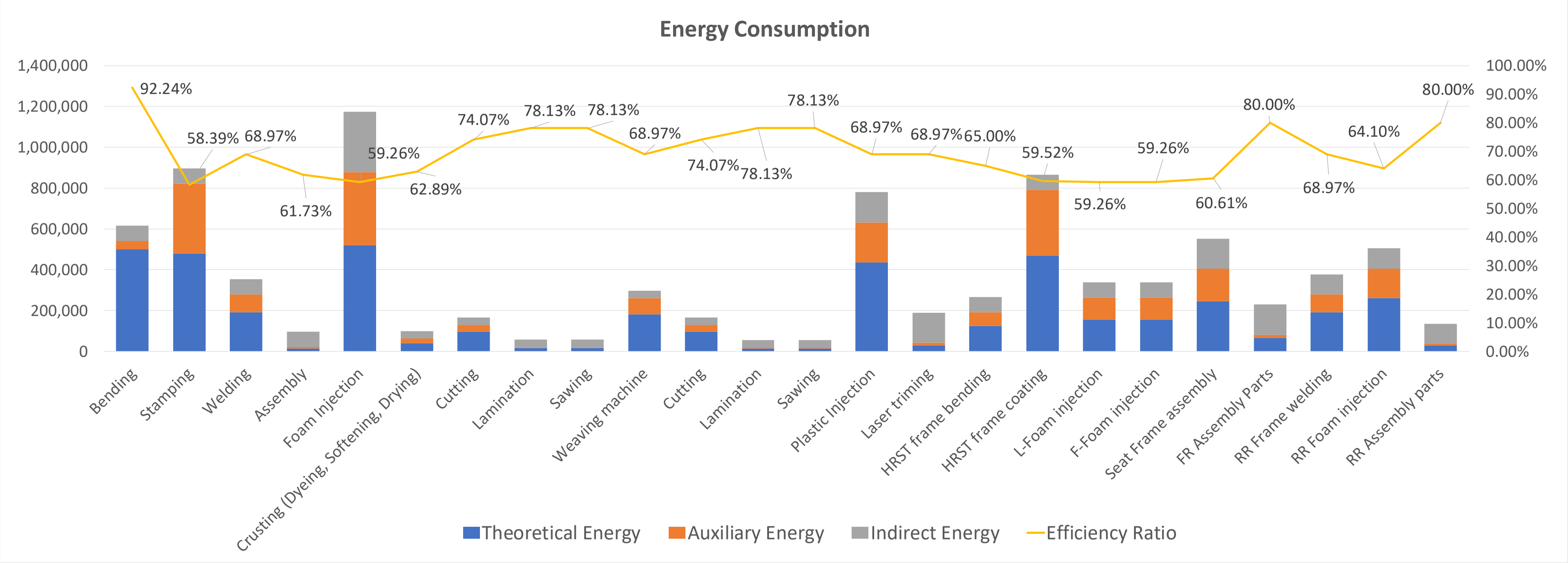


*Figure 11.13 – Result of energy consumption of each production processes*

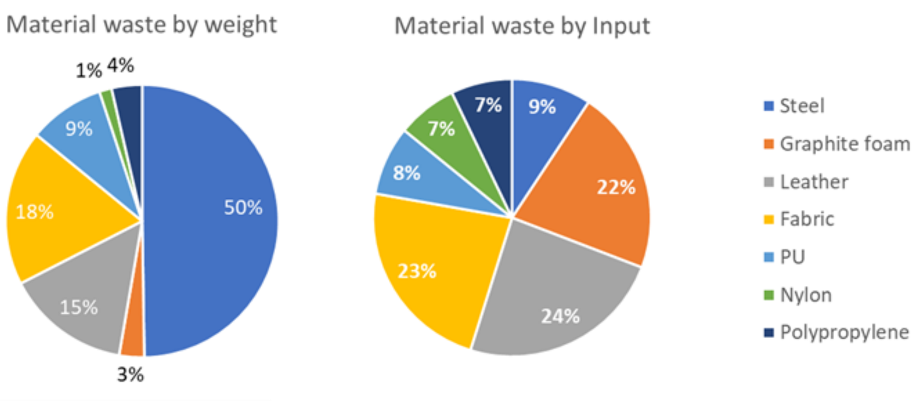


*Figure 11.14 – Result of material consumption*

#### *11.4.2.3 Identifying P&PS candidates for a co-design process*

In sum, companies A and B had a high frequency in product update (PDU = 0.64), required process change for product update, and needed to improve high material waste (for cutting processes) and energy consumption (for stamping, coating and injection processes). Therefore, referring to the classification criteria in Table 8.1, this company is suggested to further improve their resource consumption through a new single process for designing a seat together with seat production chain.

### *11.4.3 The Application of Co-Specify Phase*

At this phase, seat design and seat production development processes were analysed to identify which design decisions requires co-consideration to improve the resource efficiency of the hotspots. In this case, the complex approach of Co-specify phase involving the interrelation assessment between seat components, design processes modelling, the Ecological classification of design decisions, and the interrelation assessment between design processes were used as explained in the following subsections.

#### *11.4.3.1 The interrelation assessment between seat components*

This step demonstrates the identification of parts and components interrelations. This will be denoted as the design constraints for a Co-design process.

At the automotive-level, the interrelation between the seat and other automotive parts was identified through the interview. The design of a mounting track of a front seat is directly related to the design of a floor of the car body in which the fixing hip-points of components must be matched for the assembly, safety and ergonomic reasons. At the level of seat component, the seat component interrelation checklist was filled by a 17 years-experienced design engineer as shown in Table 11.4.

For the seat-level, a design of the front seat back frame is related to a design of front seat base frame, and the trim cover designs of the front seat and rear seat are related with each other. At the component level, in context of the part position, design of each component is only related and effect to each other within each seat part (front seat base, front seat back, rear seat).

*Table 11.4 – The result of an interrelation assessment between seat components*

Interrelation between parts for a complex product

| **Seat part/component** | | | Front seat | | | | | | | | | | | | | | | | | | Rear seat | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Front base | | | | | | | | | | | Front back | | | | | | | Rear base | | | Rear back | | |
| | | | Front Head Reststrain | Base frame | Slide rail | Mounting track | Belt buckle | Suspension | Reclining | Heater | Base Pad foam | Base Trim Covering | Plastic trim cover | Lever | Back frame | Back suspension | Airbag | Back Pad foam | Back Trim Covering | HRST support bracket | Rear Head Reststrain | Base Frame | Base Foam Pad | Base Covering | Back Frame | Back Foam Pad | Back Covering |
| Front seat | | Front Head Reststrain | ■ | | | | | | | | | | | | | | | | | | | | | | | | |
| | Front base | Base frame | | ■ | | | | × | | | × | | × | | | | | | | | | | | | | | |
| | | Slide rail | | × | ■ | × | | | | | | | | | | | | | | | | | | | | | |
| | | Mounting track | | × | × | ■ | | | | | | | | | | | | | | | | | | | | | |
| | | Belt buckle | | | | | ■ | | | | | | × | | | | | | | | | | | | | | |
| | | Suspension | | × | | | | ■ | | | × | × | | | | | | | | | | | | | | | |
| | | Reclining | | × | | | | | ■ | | | | | × | | | | | | | | | | | | | |
| | | Heater | | | | | | | | ■ | × | × | | | | | | | | | | | | | | | |
| | | Base Pad foam | | | | | × | | | × | ■ | × | × | | | | | | | | | | | | | | |
| | | Base Trim Covering | | | | | | | | × | × | ■ | × | | | × | | | × | | | | | × | | | × |
| | | Plastic trim cover | | | | | × | | | | × | × | ■ | × | | | | | | | | | | | | | |
| | | Lever | | | | | | | | | | | | ■ | | | | | | | | | | | | | |
| | Front back | Back frame | | × | | | | | | | | | | | ■ | × | | × | | | | | | | | | |
| | | Back suspension | | | | | | | | | | | | | × | ■ | | × | × | | | | | | | | |
| | | Airbag | | | | | | | | | | | | | × | | ■ | × | × | | | | | | | | |
| | | Back Pad foam | | | | | | | | | | | | | | × | × | ■ | × | | | | | | | | |
| | | Back Trim Covering | | | | | | | | | | × | | | | | × | × | ■ | | | | | × | | | × |
| | | HRST support bracket | | | | | | | | | | | | | × | | | × | | ■ | | | | | | | |
| Rear seat | | Rear Head Reststrain | | | | | | | | | | | | | | | | | | | ■ | | | | | | |
| | Rear base | Base Frame | | | | | | | | | | | | | | | | | | | | ■ | × | × | × | | |
| | | Base Foam Pad | | | | | | | | | | | | | | | | | | | | × | ■ | × | | | |
| | | Base Trim Covering | | | | | | | | | | × | | | | | | | × | | | | × | ■ | | | |
| | Rear back | Back Frame | | | | | | | | | | | | | | | | | | | | | × | | ■ | × | × |
| | | Back Foam Pad | | | | | | | | | | | | | | | | | | | | | | | | ■ | × |
| | | Back Trim Covering | | | | | | | | | | × | | | | | | | × | | | | × | × | | | ■ |

Moreover, in context of three main seat parts (seat frame, seat pad foam and seat trim covering), it was found that the design of seat frame is dominated by the design of seat pad foam and seat trim cover. This is because some design changes on the frame components (base frame, suspension, and airbag) directly require the changes of pad foam and covering design.

#### *11.4.3.2 Seat design processes modelling through PD and PSD allocation*

This automotive seat was designed based on the formal design and development processes. In a context of design complexity, during this design and development phase, all decisions related seat and seat production design are not authorised only by a small group of design engineers, but also by several sections under a design department at automotive company A and seat company B. The seat design process and the related organisation were displayed in Table 11.5. At automotive company A, the seat design department starts a new design project at the project planning stage after receiving customer requirement from the marketing department. Then, a set of seat design concepts are generated and selected by a group design staffs (product planners, styling designers, seat engineers, test engineers and package engineers). The information related this selected seat concept is transfer to the seat design engineer teams to detail the selected design with a collaboration with design engineer of seat Company B. After that the completed seat design is delivered to the three key suppliers, the prototypes of the frame, pad foam and trim covering are developed and tested. Finally, based on the approval of the test part, a prototype of the completed seat design is assembled and tested by the design departments of company A and company B.

In Table 11.6, in parallel start with seat design process, the design department of company A starts a new design project at the project planning stage by including the consideration of production constraints and supply chain strategy. At this stage, after the completion of a business agreement, company B also plans the production system and seat supply chain in collaboration with company A. Then company B starts the development of system concept based on information from seat design. After that at system detail design, company B focuses on the completion of seat part productions with the supplier companies while designers from company A concentrate on a seat production at company B and a seat assembly in vehicle production. After the completion of the detail system, part suppliers begin production ramp-up and refine the part production. Lastly, seat company B and automotive company A then perform production ramp-up and refinement.

*Table 11.5 – Seat Design process (Organisational overview)*

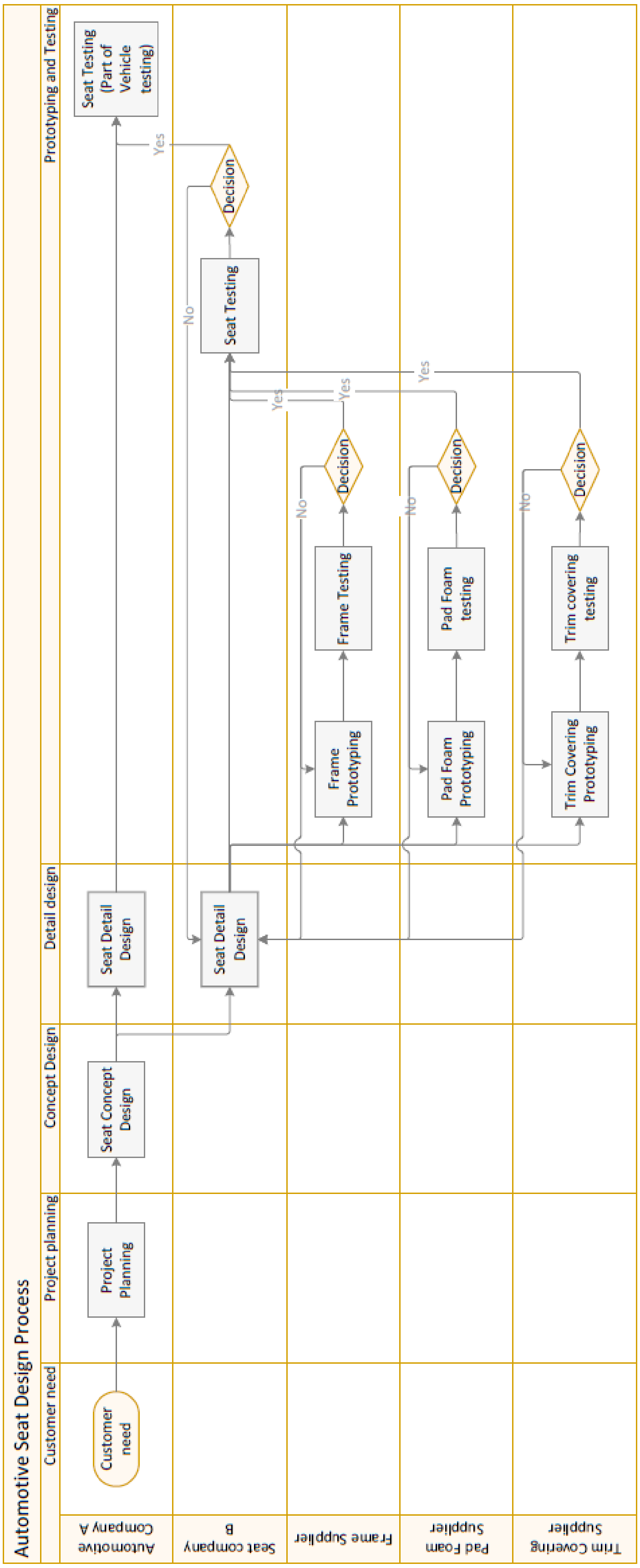
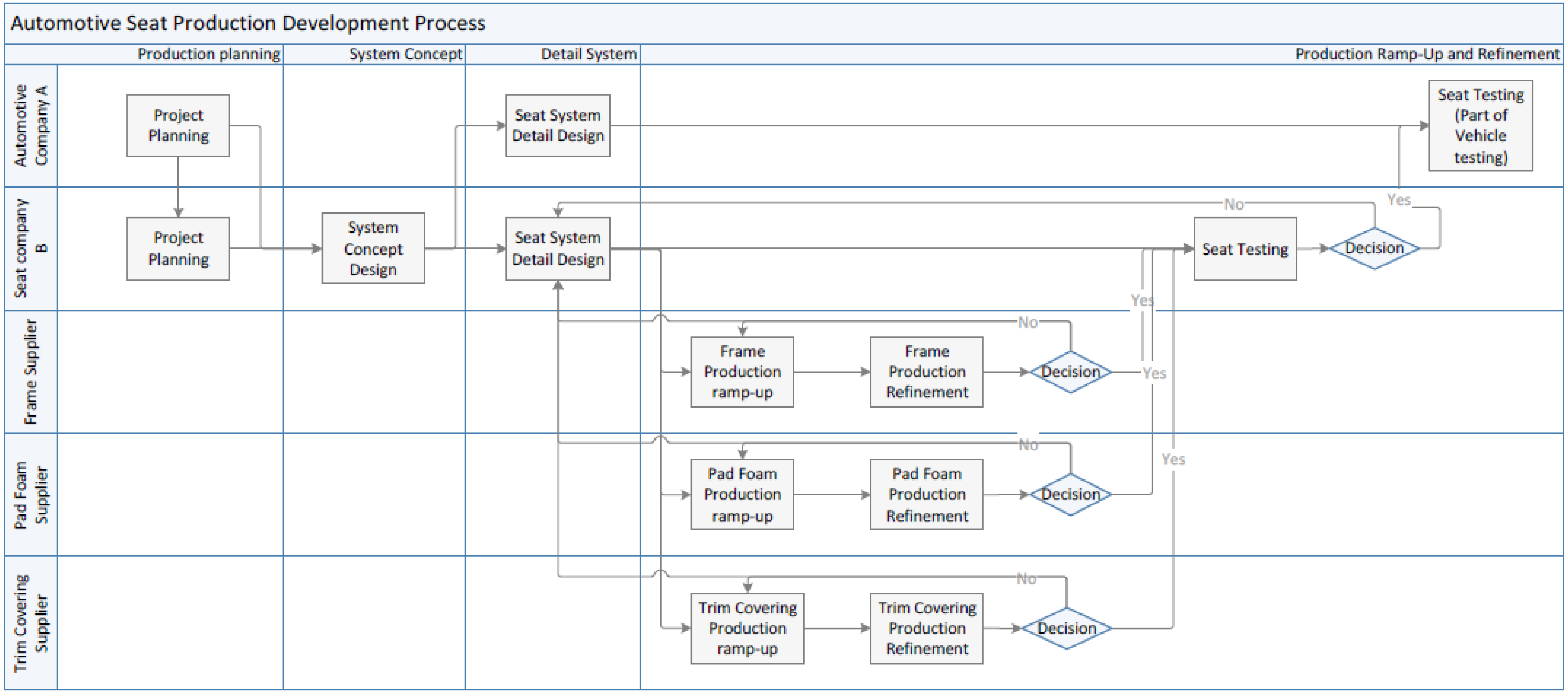


*Table 11.6 – Seat Production Development Process (Organisation overview)*



For identification of the decisions within these design processes, the design decision allocation checklists have been filled by seat design engineers (see Table 11.7 and 11.8 ). For this complex design framework approach, the design decision of automotive seat was separately allocated by the main product parts (seat frame, seat pad foam and seat trim covering). This is because each part differently focuses on a different design specification. For instance, as the allocation result, each part was considered with the different aspect of the environment during a use phase. Crash safety specification was commonly considered only on the seat frame and seat pad foam design. Moreover, it resulted that a majority of the same design specifications for different parts was considered at the same stage. At detail design stage, design engineers focus on the design of seat frame to confirm the manufacturability and safety before continuing with the detail of pad foam and trim cover.

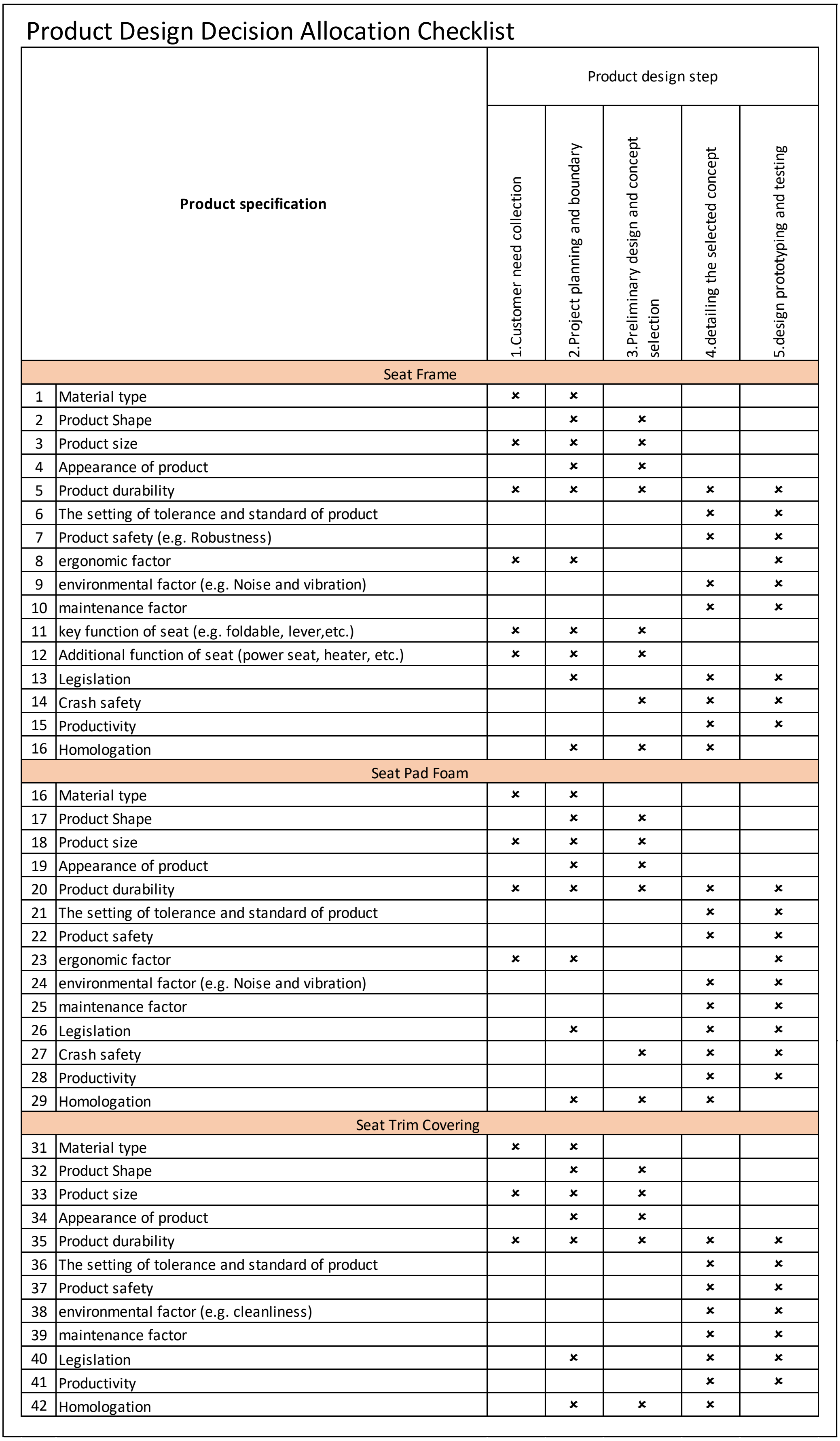
#### *11.4.3.3 Ecological identification of design decision*

After allocating the identified seat design decisions, these P&PS design decisions were classified through Ecological identification. The criteria used for this eco-classification was identified based on the result of material consumption in cutting processes, and 8 resource efficiency strategies for material elimination, material minimisation, material substitution and material separation strategy were selected as the criteria for assessing seat trim cover design decisions. As a result of the identification (see Table 11.9), all trim cover design decisions except homologation decision were needed in the considerations of these resource efficiency strategies.

In Table 11.10, 6 resource efficiency strategies within material and energy efficiency strategy were selected as criteria in the ecological identification of PSD decisions. As a result of ecological identification of PSD, decisions which influence on resource efficiency improvement can be presented in three following groups:

i. Frame design decisions: type, detail specification and source of the fabricating process.
ii. Pad foam design decisions: type, detail specification and source of the fabricating process as well as material flow process.
iii. Trim cover design decisions: type and detail specification of fabricating process, type of assembly process, the source of fabricated and assembly processes and decision-related to standard and tolerance setting.

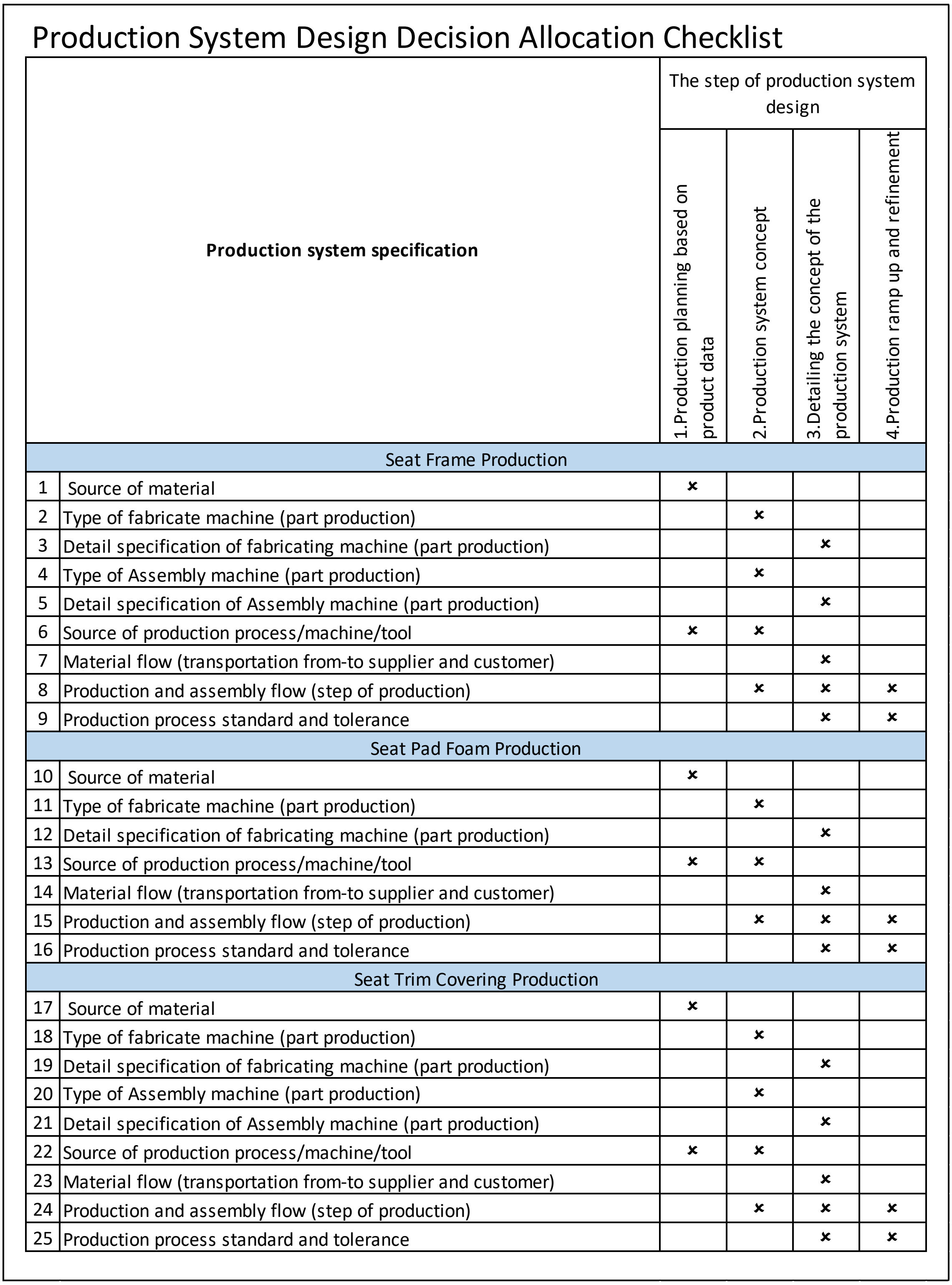
*Table 11.7 – A result of seat design decision allocation*



Product Design Decision Allocation Checklist

| **Product specification** | | Product design step | | | | |
|---|---|---|---|---|---|---|
| | | 1.Customer need collection | 2.Project planning and boundary | 3.Preliminary design and concept selection | 4.detailing the selected concept | 5.design prototyping and testing |
| Seat Frame | | | | | | |
| 1 | Material type | × | × | | | |
| 2 | Product Shape | | × | × | | |
| 3 | Product size | × | × | × | | |
| 4 | Appearance of product | | × | × | | |
| 5 | Product durability | × | × | × | × | × |
| 6 | The setting of tolerance and standard of product | | | | × | × |
| 7 | Product safety (e.g. Robustness) | | | | × | × |
| 8 | ergonomic factor | × | × | | | × |
| 9 | environmental factor (e.g. Noise and vibration) | | | | × | × |
| 10 | maintenance factor | | | | × | × |
| 11 | key function of seat (e.g. foldable, lever,etc.) | × | × | × | | |
| 12 | Additional function of seat (power seat, heater, etc.) | × | × | × | | |
| 13 | Legislation | | × | | × | × |
| 14 | Crash safety | | | × | × | × |
| 15 | Productivity | | | | × | × |
| 16 | Homologation | | × | × | × | |
| Seat Pad Foam | | | | | | |
| 16 | Material type | × | × | | | |
| 17 | Product Shape | | × | × | | |
| 18 | Product size | × | × | × | | |
| 19 | Appearance of product | | × | × | | |
| 20 | Product durability | × | × | × | × | × |
| 21 | The setting of tolerance and standard of product | | | | × | × |
| 22 | Product safety | | | | × | × |
| 23 | ergonomic factor | × | × | | | × |
| 24 | environmental factor (e.g. Noise and vibration) | | | | × | × |
| 25 | maintenance factor | | | | × | × |
| 26 | Legislation | | × | | × | × |
| 27 | Crash safety | | | × | × | × |
| 28 | Productivity | | | | × | × |
| 29 | Homologation | | × | × | × | |
| Seat Trim Covering | | | | | | |
| 31 | Material type | × | × | | | |
| 32 | Product Shape | | × | × | | |
| 33 | Product size | × | × | × | | |
| 34 | Appearance of product | | × | × | | |
| 35 | Product durability | × | × | × | × | × |
| 36 | The setting of tolerance and standard of product | | | | × | × |
| 37 | Product safety | | | | × | × |
| 38 | environmental factor (e.g. cleanliness) | | | | × | × |
| 39 | maintenance factor | | | | × | × |
| 40 | Legislation | | × | | × | × |
| 41 | Productivity | | | | × | × |
| 42 | Homologation | | × | × | × | |

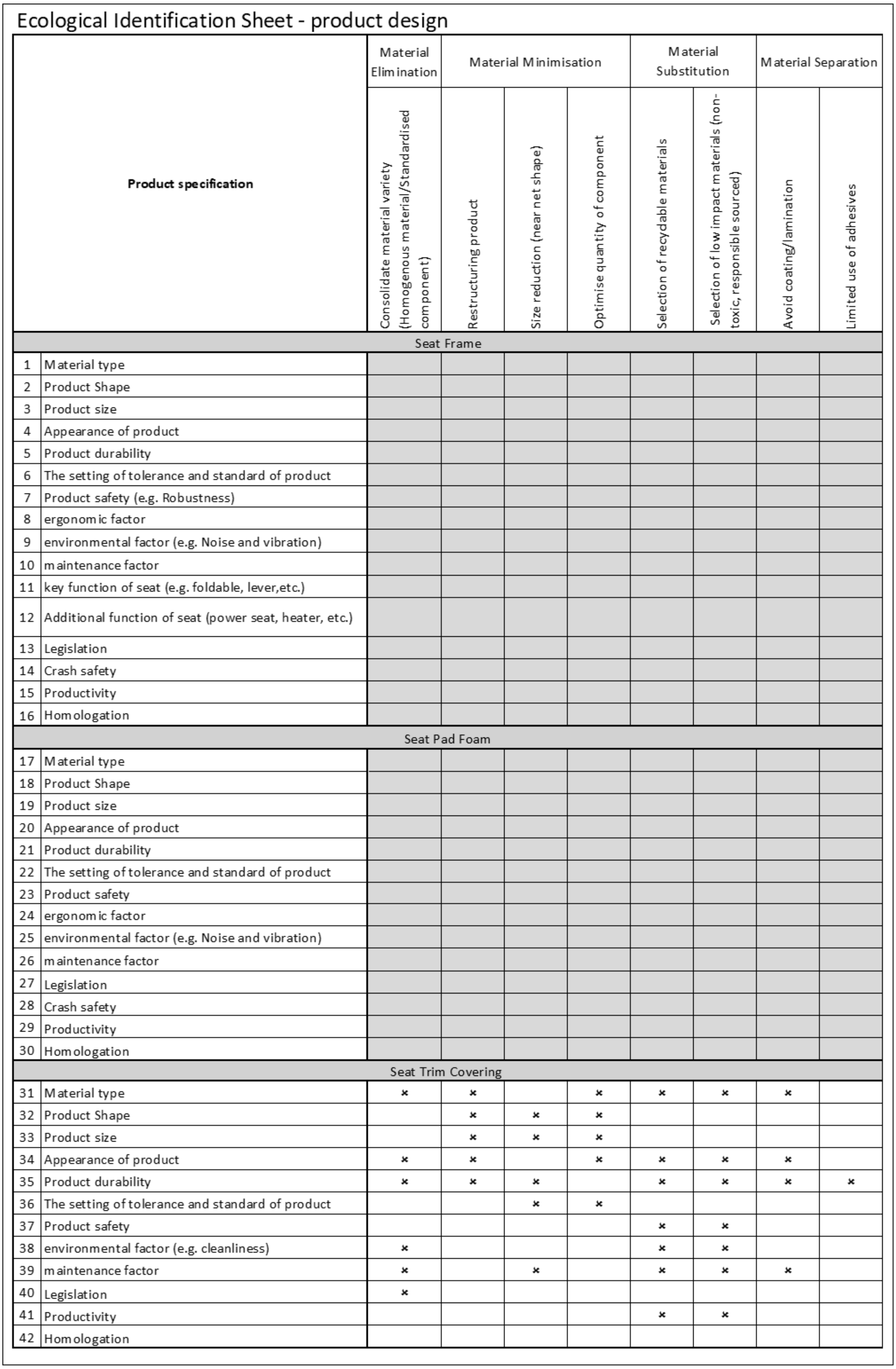
*Table 11.8 – An allocation results of the design decision of seat production*



Production System Design Decision Allocation Checklist

| | **Production system specification** | The step of production system design | | | |
|---|---|---|---|---|---|
| | | 1.Production planning based on product data | 2.Production system concept | 3.Detailing the concept of the production system | 4.Production ramp up and refinement |
| | Seat Frame Production | | | | |
| 1 | Source of material | × | | | |
| 2 | Type of fabricate machine (part production) | | × | | |
| 3 | Detail specification of fabricating machine (part production) | | | × | |
| 4 | Type of Assembly machine (part production) | | × | | |
| 5 | Detail specification of Assembly machine (part production) | | | × | |
| 6 | Source of production process/machine/tool | × | × | | |
| 7 | Material flow (transportation from-to supplier and customer) | | | × | |
| 8 | Production and assembly flow (step of production) | | × | × | × |
| 9 | Production process standard and tolerance | | | × | × |
| | Seat Pad Foam Production | | | | |
| 10 | Source of material | × | | | |
| 11 | Type of fabricate machine (part production) | | × | | |
| 12 | Detail specification of fabricating machine (part production) | | | × | |
| 13 | Source of production process/machine/tool | × | × | | |
| 14 | Material flow (transportation from-to supplier and customer) | | | × | |
| 15 | Production and assembly flow (step of production) | | × | × | × |
| 16 | Production process standard and tolerance | | | × | × |
| | Seat Trim Covering Production | | | | |
| 17 | Source of material | × | | | |
| 18 | Type of fabricate machine (part production) | | × | | |
| 19 | Detail specification of fabricating machine (part production) | | | × | |
| 20 | Type of Assembly machine (part production) | | × | | |
| 21 | Detail specification of Assembly machine (part production) | | | × | |
| 22 | Source of production process/machine/tool | × | × | | |
| 23 | Material flow (transportation from-to supplier and customer) | | | × | |
| 24 | Production and assembly flow (step of production) | | × | × | × |
| 25 | Production process standard and tolerance | | | × | × |

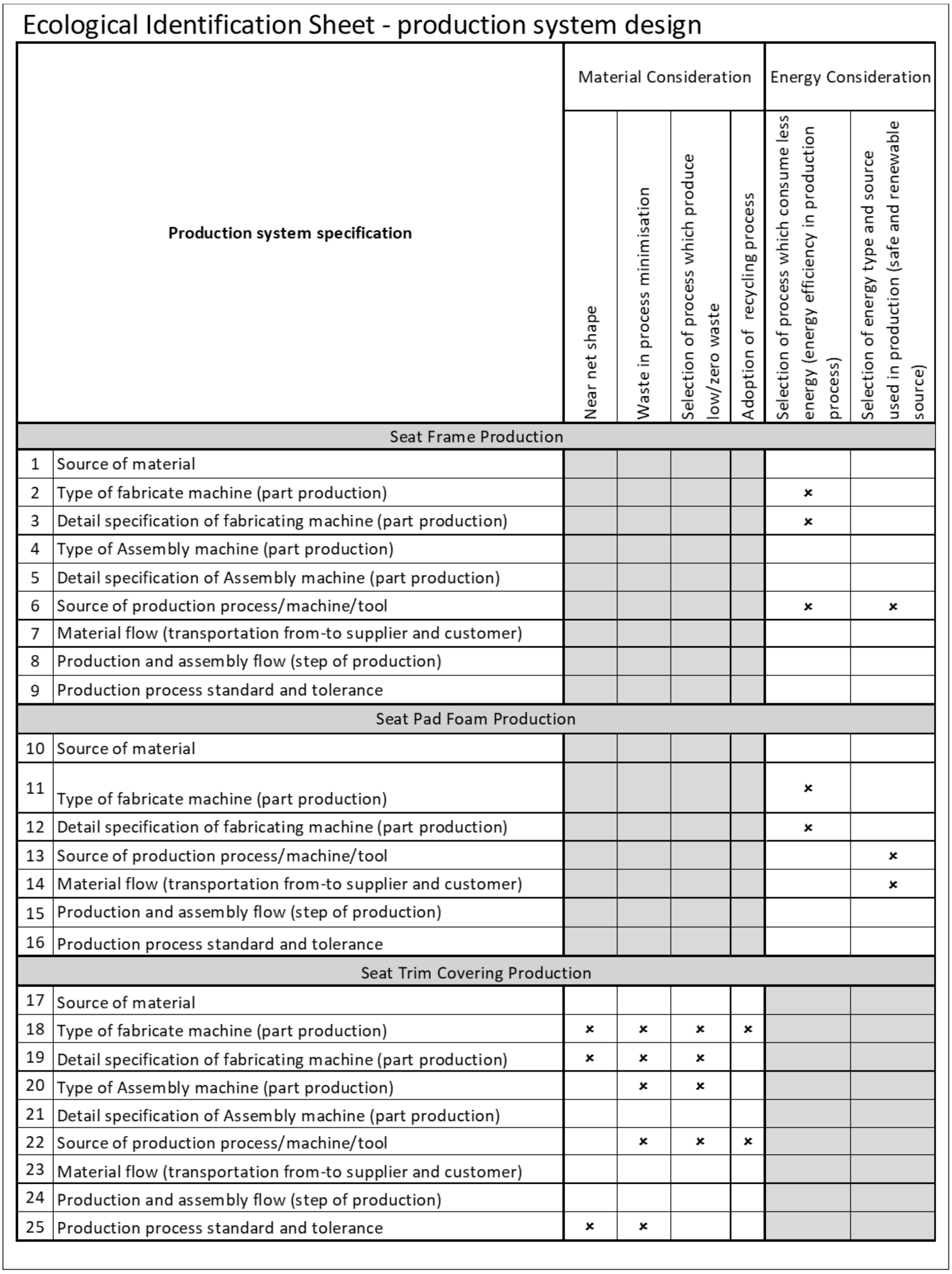
*Table 11.9 – Results of Eco-classification of PD specifications*



Ecological Identification Sheet - product design

| | **Product specification** | Material Elimination | Material Minimisation | | | Material Substitution | | Material Separation | |
|---|---|---|---|---|---|---|---|---|---|
| | | Consolidate material variety (Homogenous material/Standardised component) | Restructuring product | Size reduction (near net shape) | Optimise quantity of component | Selection of recyclable materials | Selection of low impact materials (non-toxic, responsible sourced) | Avoid coating/lamination | Limited use of adhesives |
| | Seat Frame | | | | | | | | |
| 1 | Material type | | | | | | | | |
| 2 | Product Shape | | | | | | | | |
| 3 | Product size | | | | | | | | |
| 4 | Appearance of product | | | | | | | | |
| 5 | Product durability | | | | | | | | |
| 6 | The setting of tolerance and standard of product | | | | | | | | |
| 7 | Product safety (e.g. Robustness) | | | | | | | | |
| 8 | ergonomic factor | | | | | | | | |
| 9 | environmental factor (e.g. Noise and vibration) | | | | | | | | |
| 10 | maintenance factor | | | | | | | | |
| 11 | key function of seat (e.g. foldable, lever,etc.) | | | | | | | | |
| 12 | Additional function of seat (power seat, heater, etc.) | | | | | | | | |
| 13 | Legislation | | | | | | | | |
| 14 | Crash safety | | | | | | | | |
| 15 | Productivity | | | | | | | | |
| 16 | Homologation | | | | | | | | |
| | Seat Pad Foam | | | | | | | | |
| 17 | Material type | | | | | | | | |
| 18 | Product Shape | | | | | | | | |
| 19 | Product size | | | | | | | | |
| 20 | Appearance of product | | | | | | | | |
| 21 | Product durability | | | | | | | | |
| 22 | The setting of tolerance and standard of product | | | | | | | | |
| 23 | Product safety | | | | | | | | |
| 24 | ergonomic factor | | | | | | | | |
| 25 | environmental factor (e.g. Noise and vibration) | | | | | | | | |
| 26 | maintenance factor | | | | | | | | |
| 27 | Legislation | | | | | | | | |
| 28 | Crash safety | | | | | | | | |
| 29 | Productivity | | | | | | | | |
| 30 | Homologation | | | | | | | | |
| | Seat Trim Covering | | | | | | | | |
| 31 | Material type | × | × | | × | × | × | × | |
| 32 | Product Shape | | × | × | × | | | | |
| 33 | Product size | | × | × | × | | | | |
| 34 | Appearance of product | × | × | | × | × | × | × | |
| 35 | Product durability | × | × | × | | × | × | × | × |
| 36 | The setting of tolerance and standard of product | | | × | × | | | | |
| 37 | Product safety | | | | | × | × | | |
| 38 | environmental factor (e.g. cleanliness) | × | | | | × | × | | |
| 39 | maintenance factor | × | | × | | × | × | × | |
| 40 | Legislation | × | | | | | | | |
| 41 | Productivity | | | | | × | × | | |
| 42 | Homologation | | | | | | | | |

*Table 11.10 – Results of Eco-classification of PSD specifications*



Ecological Identification Sheet - production system design

| | **Production system specification** | Material Consideration | | | | Energy Consideration | |
|---|---|---|---|---|---|---|---|
| | | Near net shape | Waste in process minimisation | Selection of process which produce low/zero waste | Adoption of recycling process | Selection of process which consume less energy (energy efficiency in production process) | Selection of energy type and source used in production (safe and renewable source) |
| | Seat Frame Production | | | | | | |
| 1 | Source of material | | | | | | |
| 2 | Type of fabricate machine (part production) | | | | | × | |
| 3 | Detail specification of fabricating machine (part production) | | | | | × | |
| 4 | Type of Assembly machine (part production) | | | | | | |
| 5 | Detail specification of Assembly machine (part production) | | | | | | |
| 6 | Source of production process/machine/tool | | | | | × | × |
| 7 | Material flow (transportation from-to supplier and customer) | | | | | | |
| 8 | Production and assembly flow (step of production) | | | | | | |
| 9 | Production process standard and tolerance | | | | | | |
| | Seat Pad Foam Production | | | | | | |
| 10 | Source of material | | | | | | |
| 11 | Type of fabricate machine (part production) | | | | | × | |
| 12 | Detail specification of fabricating machine (part production) | | | | | × | |
| 13 | Source of production process/machine/tool | | | | | | × |
| 14 | Material flow (transportation from-to supplier and customer) | | | | | | × |
| 15 | Production and assembly flow (step of production) | | | | | | |
| 16 | Production process standard and tolerance | | | | | | |
| | Seat Trim Covering Production | | | | | | |
| 17 | Source of material | | | | | | |
| 18 | Type of fabricate machine (part production) | × | × | × | × | | |
| 19 | Detail specification of fabricating machine (part production) | × | × | × | | | |
| 20 | Type of Assembly machine (part production) | | × | × | | | |
| 21 | Detail specification of Assembly machine (part production) | | | | | | |
| 22 | Source of production process/machine/tool | | × | × | × | | |
| 23 | Material flow (transportation from-to supplier and customer) | | | | | | |
| 24 | Production and assembly flow (step of production) | | | | | | |
| 25 | Production process standard and tolerance | × | × | | | | |

#### *11.4.3.4 Assessment of Interrelation between P&PS design decisions*

Based on the identified design specifications, the interrelation mapping sheets were established and delivered to test their applicability by a collaborative seat design engineer. To complete these checklists, a design engineer was asked to select which PSD data is required for making a selection/decision of a particular PD specification. The filled Eco-interrelation mapping check sheets are illustrated in Appendix D, and the calculated mapping results are presented in Figure 11.15. As a result, it was found that 34 out of 48 of PD decisions were specified as the co-design specifications. For seat frame design, all decisions except ergonomic factor, crash safety and homologation were specified as the co-design decisions. For seat pad foam, all decisions except durability, environmental factor (e.g. cleanliness), functions of the seat, crash safety and homologation were specified as the co-design decisions. For seat trim cover, all decisions except ergonomic factor, functions of seat and crash safety were specified as the co-design decisions, In the same way, 15 out of 27 PSD decisions were also defined as the co-design specifications. The decision related to a type, detail spec and a source of frame and pad foam fabrication process and all production specifications of the trim cover was specified as the co-design decisions.

#### *11.4.3.5 A recommendation of the most suitable co-create strategy*

As a result of the interrelation assessment, these companies were suggested to create and implement a new single process for co-designing these automotive seats and their production system by using the Adaptation strategy since 56% of production system design decision was advised to co-considered with product decision within the complex design process.

### *11.4.4 The application of Co-Create phase*

Through Adaptation strategy, these company A and B were advised to implement i) the improvement of knowledge and information interchange, ii) strengthening design collaboration and iii) generating new co-design processes as follows.

At the former step, based on the current practice, this company was recommended to provide training courses related to P&PS design, sustainability, and resource efficiency so that these designers could be reskilled to understand all necessary knowledge for implementing a co-design

| Product: Seat Frame | | Seat Frame Production | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 1. Source of material | 2. Type of fabricate machine (part production) | 3. Detail specification of fabricating machine (part production) | 4. Type of Assembly machine (part production) | 5. Detail specification of Assembly machine (part production) | 6. Source of production process/machine/tool | 7. Material flow (transportation from-to supplier and customer) | 8. Production and assembly flow (step of production) | 9. Production process standard and tolerance |
| Seat Frame | Material type | 0 | 1 | 1 | 0 | 0 | 1 | 0 | 0 | 0 |
| | Product Shape | 0 | 1 | 1 | 0 | 0 | 1 | 0 | 0 | 0 |
| | Product size | 0 | 1 | 1 | 0 | 0 | 1 | 0 | 0 | 0 |
| | Appearance of product | 0 | 1 | 1 | 0 | 0 | 1 | 0 | 0 | 0 |
| | Product durability | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| | The setting of tolerance and standard of product | 0 | 1 | 1 | 0 | 0 | 1 | 0 | 0 | 0 |
| | Product safety (e.g. Robustness) | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| | ergonomic factor | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | environmental factor (e.g. Noise and vibration) | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 |
| | maintenance factor | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| | key function of seat (e.g. foldable, lever,etc.) | 0 | 1 | 1 | 0 | 0 | 1 | 0 | 0 | 0 |
| | Additional function of seat (power seat, heater, etc.) | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 |
| | Legislation | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 |
| | Crash safety | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Productivity | 0 | 1 | 1 | 0 | 0 | 1 | 0 | 0 | 0 |
| | Homologation | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

| Product: Seat Pad Foam | | Seat Pad Foam Production | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 1. Source of material | 2. Type of fabricate machine (part production) | 3. Detail specification of fabricating machine (part production) | 4. Type of Assembly machine (part production) | 5. Detail specification of Assembly machine (part production) | 6. Source of production process/machine/tool | 7. Material flow (transportation from-to supplier and customer) | 8. Production and assembly flow (step of production) | 9. Production process standard and tolerance |
| Seat Pad Foam | Material type | 0 | 1 | 1 | 0 | 0 | 1 | 0 | 0 | 0 |
| | Product Shape | 0 | 1 | 1 | 0 | 0 | 1 | 0 | 0 | 0 |
| | Product size | 0 | 1 | 1 | 0 | 0 | 1 | 0 | 0 | 0 |
| | Appearance of product | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Product durability | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | The setting of tolerance and standard of product | 0 | 1 | 1 | 0 | 0 | 1 | 0 | 0 | 0 |
| | Product safety (e.g. Robustness) | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| | ergonomic factor | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| | environmental factor (e.g. Noise and vibration) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | maintenance factor | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| | key function of seat (e.g. foldable, lever,etc.) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Additional function of seat (power seat, heater, etc.) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Legislation | 0 | 1 | 1 | 0 | 0 | 1 | 0 | 0 | 0 |
| | Crash safety | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Productivity | 0 | 1 | 1 | 0 | 0 | 1 | 0 | 0 | 0 |
| | Homologation | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

| Product: Seat Trim Covering | | Seat Trim Covering Production | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 1. Source of material | 2. Type of fabricate machine (part production) | 3. Detail specification of fabricating machine (part production) | 4. Type of Assembly machine (part production) | 5. Detail specification of Assembly machine (part production) | 6. Source of production process/machine/tool | 7. Material flow (transportation from-to supplier and customer) | 8. Production and assembly flow (step of production) | 9. Production process standard and tolerance |
| Seat Trim Covering | Material type | 1 | 2 | 2 | 2 | 1 | 2 | 1 | 1 | 2 |
| | Product Shape | 0 | 0 | 2 | 0 | 1 | 1 | 0 | 0 | 2 |
| | Product size | 0 | 0 | 2 | 0 | 1 | 1 | 0 | 0 | 2 |
| | Appearance of product | 1 | 2 | 2 | 2 | 1 | 1 | 0 | 0 | 2 |
| | Product durability | 1 | 2 | 2 | 1 | 1 | 0 | 0 | 0 | 2 |
| | The setting of tolerance and standard of product | 0 | 2 | 2 | 2 | 1 | 1 | 0 | 0 | 2 |
| | Product safety (e.g. Robustness) | 1 | 0 | 2 | 1 | 1 | 0 | 0 | 1 | 2 |
| | ergonomic factor | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | environmental factor (e.g. Noise and vibration) | 1 | 1 | 2 | 1 | 1 | 0 | 0 | 1 | 2 |
| | maintenance factor | 1 | 0 | 1 | 0 | 1 | 0 | 0 | 0 | 2 |
| | key function of seat (e.g. foldable, lever,etc.) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Additional function of seat (power seat, heater, etc.) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Legislation | 0 | 1 | 2 | 1 | 1 | 1 | 0 | 0 | 2 |
| | Crash safety | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Productivity | 0 | 2 | 2 | 2 | 1 | 1 | 1 | 1 | 2 |
| | Homologation | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |

*Figure 11.15 – Results of interrelation assessment between PD and PSD of the seat frame, seat pad foam and seat trim covering*

process. Moreover, the information related to P&PS design decisions should be documented, updated, and distributed to all relevant designers.

Then, design collaboration practice between product designers and production system designers (within and between company A and B) should be evaluated, improved and practised at 'collaboration level' (see section 9.4.1). Significantly, after the improvement of knowledge and information interchange as well as design collaboration, P&PS designers were repositioned into a one design team under a single design section.

After these improvements, the reskilled designers can perform co-design activities through a new co-design process as illustrated in Table 11.11 – 11.13. This new P&PS co-design processes need to be documented and distributed to all relevant designers and stakeholders to enable co-design consideration in this central design and central control practice.

### *11.4.5 Result and discussion of case study 2*

The study of co-design feasibility suggests that this company A and B should adopt a single co-design process in designing a new seat model and its production system concurrently. This is because the study found that the company A and B was often updated seat and seat production design with high design update rate (PDU=0.64). Significantly, there is a need to include the consideration of resource efficiency – especially material efficiency of trim covering cutting process and energy efficiency of pad foam injection, frame stamping and coating processes – into the early stage of design process. Furthermore, the information and design decision of seat production system should be considered in concert with seat design as presented in the result of design process assessment in order to improve the hotspot processes. Therefore, it is suggested transforming these seat and seat production design processes by using Adaptation method because of the complication in co-designing many decisions under the complex design processes with distributed design and distributed control scenario. To implement the changes through this strategy, in this case, the significant challenge is not only the changes within one organisation but also the need to strengthen collaboration and create close collaboration between two firms. Besides, there is a need for a clear agreement to manage the sensitive design knowledge and information exchanging between two firms.

*Table 11.11 – A new seat co-design process for designing seat and seat production together through a rearrangement of design decisions*

| Decision of Design Specification | | | stage | 5 | 25 | 48 | 9 | 1 | 2 | 8 | 24 | 50 | 7 | 6 | 31 | 4 | 32 | 30 | 29 | 3 | 49 | 57 | 28 | 14 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 5 | Frame | ergonomic factor | 2 | ■ | | | | | | | | | | | | | | | | | | | | | |
| 25 | Frame | Homologation | 3 | | ■ | | | | | | | | | | | | | | | | | | | | |
| 48 | Frame | Type of fabricate machine (part production) | 7 | | | ■ | | x | x | x | | | | | | | x | | | x | | | | | |
| 9 | Frame | Product durability | all | | | 2 | ■ | x | x | | | | | | | | | | | | | 2 | | | |
| 1 | Frame | Material type | 2 | | x | 2 | x | ■ | | x | x | 2 | | | | x | x | x | x | | | 2 | | | |
| 2 | Frame | Product Shape | 2 | | x | 2 | x | x | ■ | x | x | 2 | | | | | x | x | x | x | | 2 | | | |
| 8 | Frame | Legislation | 2 | | | | | x | x | ■ | | 2 | | | | | | | | x | | | | | |
| 24 | Frame | Crash safety | 3 | | x | | x | x | x | x | ■ | | | | | | | | | x | | | | | |
| 50 | Frame | Source of production process/machine/tool | 7 | | | x | | x | x | | | ■ | | | | | x | | | x | x | | | | |
| 7 | Frame | Additional function of seat (power seat, heater, etc.) | 2 | x | | | | | | | | 2 | ■ | | | | | | | | | | | | |
| 6 | Frame | key function of seat (e.g. foldable, lever,etc.) | 2 | x | | 2 | | | | | | 2 | | ■ | | | | | | | | 2 | | | |
| 31 | Frame | maintenance factor | 4 | | | 2 | x | x | x | | | | x | x | ■ | | | | | | | 2 | | | |
| 4 | Frame | Appearance of product | 2 | | | 2 | x | | | | | 2 | | | | ■ | | | | | | 2 | | | |
| 32 | Frame | Productivity | 4 | | | 2 | | x | x | | | 2 | | | | x | ■ | | | x | | 2 | | | |
| 30 | Frame | environmental factor (e.g. Noise and vibration) | 4 | | | | | x | x | | | 2 | | | | | | ■ | | x | | | x | | |
| 29 | Frame | Product safety (e.g. Robustness) | 4 | | x | 2 | | x | | x | x | | | | x | | | x | ■ | | | 2 | x | | |
| 3 | Frame | Product size | 2 | x | x | 2 | x | | x | x | x | 2 | x | x | | | x | x | x | ■ | | 2 | | | |
| 49 | Frame | Type of Assembly machine (part production) | 7 | | | | | x | x | x | | | | | | | x | | | x | ■ | | | | |
| 57 | Frame | Detail specification of fabricating machine (part production) | 8 | | | x | | x | x | | x | x | | | x | | | x | x | x | x | ■ | | | |
| 28 | Frame | The setting of tolerance and standard of product | 4 | | | 2 | | x | x | x | | 2 | x | x | x | x | x | | | x | | 2 | ■ | | |
| 14 | Pad foam | Legislation | 2 | | | | | | | | | | | | | | | | | | | | | ■ | |
| 10 | Pad foam | Product Shape | 2 | | | | | | x | | | | | | | | | | | | | | | x | ■ |
| 11 | Pad foam | Product size | 2 | | | | | | | | | | | | | | | | | x | | | | x | |
| 12 | Pad foam | Appearance of product | 2 | x | | | | | | | | | | | | | | | | | | | | x | |
| 37 | Pad foam | Productivity | 4 | | | | | | | | | | | | | | | | | | | | | | x |
| 52 | Pad foam | Type of fabricate machine (part production) | 7 | | | | | | | | | | | | | | | | | | | | | | x |
| 45 | Pad foam | Source of production process/machine/tool | 6 | | | | | | | | | | | | | | | | | | | | | | x |
| 61 | Pad foam | Detail specification of fabricating machine (part production) | 8 | | | | | | | | | | | | | | | | | | | | | x | x |
| 13 | Pad foam | ergonomic factor | 2 | x | | | | | | | | | | | | | | | | | | | | | |
| 16 | Pad foam | Product durability | all | | | | | | | | | | | | | | | | | | | | | | x |
| 15 | Pad foam | Homologation | 2 | | | | | | | | | | | | | | | | | | | | | x | x |
| 26 | Pad foam | Material type | 3 | | | | | | | | | | | | | | | | | | | | | x | |
| 43 | Frame | Source of material | 6 | | | | | x | | | | | | | | | x | | | | | | | | |
| 44 | Pad foam | Source of material | 6 | | | | | | | | | | | | | | | | | | | | | | |
| 62 | Pad foam | Material flow (transportation from-to supplier and customer) | 8 | | | | | | | | | x | | | | | | | | | | | | | |
| 58 | Frame | Detail specification of Assembly machine (part production) | 8 | | | x | | x | x | | x | x | | | x | | | x | x | x | x | | | | |
| 59 | Frame | Material flow (transportation from-to supplier and customer) | 8 | | | | | | | | | x | | | | | | | | | | | | | |
| 60 | Frame | Production process standard and tolerance | 8 | | | x | | x | x | | | | | | | | | | | x | x | x | | | |
| 51 | Frame | Production and assembly flow (step of production) | 7 | | | | | x | x | | | x | | | | | x | | | x | x | | | | |
| 27 | Pad foam | Crash safety | 3 | | | | | | | | | | | | | | | | | | | | | x | |
| 33 | Pad foam | The setting of tolerance and standard of product | 4 | | | | | | | | | | | | | | | | | | | | | x | x |
| 34 | Pad foam | Product safety (e.g. Robustness) | 4 | | | | | | | | | | | | | | | | | | | | | | |
| 35 | Pad foam | environmental factor (e.g. Noise and vibration) | 4 | | | | | | | | | | | | | | | | | | | | | | x |
| 66 | Trim coverin | Material flow (transportation from-to supplier and customer) | 8 | | | | | | | | | x | | | | | | | | | | | | | |
| 56 | Trim coverin | Production and assembly flow (step of production) | 7 | | | | | | | | | | | | | | | | | | | | | | |
| 63 | Pad foam | Production process standard and tolerance | 8 | | | | | | | | | | | | | | | | | | | | | | |
| 20 | Trim coverin | Appearance of product | 2 | | | | | | | | | | | | | | | | | | | | | | x |
| 64 | Trim coverin | Detail specification of fabricating machine (part production) | 8 | | | | | | | | | | | | | | | | | | | | | | |
| 65 | Trim coverin | Detail specification of Assembly machine (part production) | 8 | | | | | | | | | | | | | | | | | | | | | | |
| 67 | Trim coverin | Production process standard and tolerance | 8 | | | | | | | | | | | | | | | | | | | | | | |
| 21 | Trim coverin | Legislation | 2 | | | | | | | | x | | | | | | | | | | | | | | |
| 22 | Trim coverin | Homologation | 2 | | | | | | | | | | | | | | | | | | | | | | |
| 23 | Trim coverin | Product durability | all | | | | | | | | | | | | | | | | | | | | | | |
| 17 | Trim coverin | Material type | 2 | | | | | | | | | | | | | | | | | | | | | | |
| 46 | Trim coverin | Source of material | 6 | | | | | | | | | | | | | | | | | | | | | | |
| 18 | Trim coverin | Product Shape | 2 | | | | | | | | | | | | | | | | | | | | | | x |
| 19 | Trim coverin | Product size | 2 | | | | | | | | | | | | | | | | | | | | | | x |
| 42 | Trim coverin | Productivity | 4 | | | | | | | | | | | | | | | | | | | | | | |
| 47 | Trim coverin | Source of production process/machine/tool | 6 | | | | | | | | | | | | | | | | | | | | | | |
| 54 | Trim coverin | Type of fabricate machine (part production) | 7 | | | | | | | | | | | | | | | | | | | | | | |
| 55 | Trim coverin | Type of Assembly machine (part production) | 7 | | | | | | | | | | | | | | | | | | | | | | |
| 36 | Pad foam | maintenance factor | 4 | | | | | | | | | | | | | | | | | | | | | x | x |
| 38 | Trim coverin | The setting of tolerance and standard of product | 4 | | | | | | | | | | | | | | | | | | | | | | |
| 39 | Trim coverin | Product safety | 4 | | | | | | | | | | | | | | | | | | | | | | |
| 40 | Trim coverin | environmental factor (e.g. Noise and vibration, cleanliness) | 4 | | | | | | | | | | | | | | | | | | | | | | |
| 41 | Trim coverin | maintenance factor | 4 | | | | | | | | | | | | | | | | | | | | | | |
| 53 | Pad foam | Production and assembly flow (step of production) | 7 | | | | | | | | | x | | | | | | | | | | | | | |

*Table 11.12 – A new seat co-design process for designing seat and seat production together through a rearrangement of design decisions (Continue 2)*

| Decision of Design Specification | | | stage | 11 | 12 | 37 | 52 | 45 | 61 | 13 | 16 | 15 | 26 | 43 | 44 | 62 | 58 | 59 | 60 | 51 | 27 | 33 | 34 | 35 | 20 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 5 | Frame | ergonomic factor | 2 | | | | | | | | | | | | | | | | | | | | | | |
| 25 | Frame | Homologation | 3 | | | | | | | | | | | | | | | | | | | | | | |
| 48 | Frame | Type of fabricate machine (part production) | 7 | | | | | | | | | | | | | | | | | | | | | | |
| 9 | Frame | Product durability | all | | | | | | | | | | | | | | | | | | | | | | |
| 1 | Frame | Material type | 2 | | | | | | | | | | | | | | | | | | | | | | |
| 2 | Frame | Product Shape | 2 | | | | | | | | | | | | | | | | | | | | | | |
| 8 | Frame | Legislation | 2 | | | | | | | | | | | | | | | | | | | | | | |
| 24 | Frame | Crash safety | 3 | | | | | | | | | | | | | | | | | | | | | | |
| 50 | Frame | Source of production process/machine/tool | 7 | | | | | | | | | | | | | | | | | | | | | | |
| 7 | Frame | Additional function of seat (power seat, heater, etc.) | 2 | | | | | | | | | | | | | | | | | | | | | | |
| 6 | Frame | key function of seat (e.g. foldable, lever,etc.) | 2 | | | | | | | | | | | | | | | | | | | | | | |
| 31 | Frame | maintenance factor | 4 | | | | | | | | | | | | | | | | | | | | | | |
| 4 | Frame | Appearance of product | 2 | | | | | | | | | | | | | | | | | | | | | | |
| 32 | Frame | Productivity | 4 | | | | | | | | | | | | | | | | | | | | | | |
| 30 | Frame | environmental factor (e.g. Noise and vibration) | 4 | | | | | | | | | | | | | | | | | | | | | | |
| 29 | Frame | Product safety (e.g. Robustness) | 4 | | | | | | | | | | | | | | | | | | | | | | |
| 3 | Frame | Product size | 2 | | | | | | | | | | | | | | | | | | | | | | |
| 49 | Frame | Type of Assembly machine (part production) | 7 | | | | | | | | | | | | | | | | | | | | | | |
| 57 | Frame | Detail specification of fabricating machine (part production) | 8 | | | | | | | | | | | | | | | | | | | | | | |
| 28 | Frame | The setting of tolerance and standard of product | 4 | | | | | | | | | | | | | | | | | | | | | | |
| 14 | Pad foam | Legislation | 2 | | | | 2 | 2 | 2 | | | | | | | | | | | | | | | | |
| 10 | Pad foam | Product Shape | 2 | | | | 2 | 2 | 2 | | | | | | | | | | | | | | | | |
| 11 | Pad foam | Product size | 2 | ■ | | | 2 | 2 | 2 | | | | | | | | | | | | | | | | |
| 12 | Pad foam | Appearance of product | 2 | | ■ | | 2 | | 2 | x | | | | | | | | | | | | | | | |
| 37 | Pad foam | Productivity | 4 | x | | ■ | 2 | 2 | 2 | | | | x | | | | | | | | | | | | |
| 52 | Pad foam | Type of fabricate machine (part production) | 7 | x | | x | ■ | | | | | | | | | | | | | | | | | | |
| 45 | Pad foam | Source of production process/machine/tool | 6 | x | | x | | ■ | | | | | x | | | | | | | | | | | | |
| 61 | Pad foam | Detail specification of fabricating machine (part production) | 8 | x | x | | | | ■ | | x | | | | | | | | | | | | | | |
| 13 | Pad foam | ergonomic factor | 2 | | | | 2 | | 2 | ■ | | | | | | | | | | | | | | | |
| 16 | Pad foam | Product durability | all | x | x | | | | | x | ■ | | | | | | | | | | | | | | |
| 15 | Pad foam | Homologation | 2 | x | | | | | | | | ■ | | | | | | | | | | | | | |
| 26 | Pad foam | Material type | 3 | | x | | 2 | 2 | 2 | | x | x | ■ | | | | | | | | | | | | |
| 43 | Frame | Source of material | 6 | | | | | | | | | | | ■ | | | | | | | | | | | |
| 44 | Pad foam | Source of material | 6 | | | x | | | | | | | x | | ■ | | | | | | | | | | |
| 62 | Pad foam | Material flow (transportation from-to supplier and customer) | 8 | | | | | x | | | | | | x | x | ■ | | | | | | | | | |
| 58 | Frame | Detail specification of Assembly machine (part production) | 8 | | | | | | | | | | | | | | ■ | | | | | | | | |
| 59 | Frame | Material flow (transportation from-to supplier and customer) | 8 | | | | | | | | | | | x | | | | ■ | | | | | | | |
| 60 | Frame | Production process standard and tolerance | 8 | | | | | | | | | | | | | | x | | ■ | | | | | | |
| 51 | Frame | Production and assembly flow (step of production) | 7 | | | | | | | | | | | x | | | | | | ■ | | | | | |
| 27 | Pad foam | Crash safety | 3 | | | | | | | | | | | | | | | | | | ■ | | | | |
| 33 | Pad foam | The setting of tolerance and standard of product | 4 | x | x | x | 2 | 2 | 2 | | | | x | | | | | | | | | ■ | | | |
| 34 | Pad foam | Product safety (e.g. Robustness) | 4 | | | | 2 | | 2 | | | | | | | | | | | | x | | ■ | | |
| 35 | Pad foam | environmental factor (e.g. Noise and vibration) | 4 | x | x | | | | | | x | | x | | | | | | | | | | | ■ | |
| 20 | Trim coverin | Appearance of product | 2 | x | | | | | | | | | | | | | | | | | | | | | ■ |
| 64 | Trim coverin | Detail specification of fabricating machine (part production) | 8 | | | | | | | | | | | | | | | | | | | | | | x |
| 65 | Trim coverin | Detail specification of Assembly machine (part production) | 8 | | | | | | | | | | | | | | | | | | | | | | x |
| 67 | Trim coverin | Production process standard and tolerance | 8 | | | | | | | | | | | | | | | | | | | | | | x |
| 21 | Trim coverin | Legislation | 2 | | | | | | | | | | | | | | | | | | | | | | |
| 22 | Trim coverin | Homologation | 2 | | | | | | | | | | | | | | | | | | | | | | |
| 23 | Trim coverin | Product durability | all | | | | | | | | | | | | | | | | | | | | | | |
| 46 | Trim coverin | Source of material | 6 | | | | | | | | | | | | | | | | | | | | | | |
| 18 | Trim coverin | Product Shape | 2 | x | | | | | | | | | | | | | | | | | | | | | |
| 19 | Trim coverin | Product size | 2 | | | | | | | | | | | | | | | | | | | | | | |
| 42 | Trim coverin | Productivity | 4 | | | | | | | | | | | | | | | | | | | | | | |
| 47 | Trim coverin | Source of production process/machine/tool | 6 | | | | | | | | | | | | | | | | | | | | | | |
| 54 | Trim coverin | Type of fabricate machine (part production) | 7 | | | | | | | | | | | | | | | | | | | | | | |
| 55 | Trim coverin | Type of Assembly machine (part production) | 7 | | | | | | | | | | | | | | | | | | | | | | |
| 66 | Trim coverin | Material flow (transportation from-to supplier and customer) | 8 | | | | | x | | | | | | x | x | | | | | | | | | | |
| 56 | Trim coverin | Production and assembly flow (step of production) | 7 | | | | | x | | | | | | x | x | x | | | | | | | | | |
| 17 | Trim coverin | Material type | 2 | | | | | | | | | | | | | | | | | | | | | | x |
| 63 | Pad foam | Production process standard and tolerance | 8 | | | x | x | | x | | | | | | | | | | | | | x | | x | |
| 36 | Pad foam | maintenance factor | 4 | x | x | | 2 | | 2 | | x | | x | | | | | | | | | | x | x | |
| 38 | Trim coverin | The setting of tolerance and standard of product | 4 | | | | | | | | | | | | | | | | | | | | | | x |
| 39 | Trim coverin | Product safety | 4 | | | | | | | | | | | | | | | | | | | | | | |
| 40 | Trim coverin | environmental factor (e.g. Noise and vibration, cleanliness) | 4 | | | | | | | | | | | | | | | | | | | | | | x |
| 41 | Trim coverin | maintenance factor | 4 | | | | | | | | | | | | | | | | | | | | | | |
| 53 | Pad foam | Production and assembly flow (step of production) | 7 | | | | x | x | | | | | | x | x | | | | | x | | | | | |

*Table 11.13 – A new seat co-design process for designing seat and seat production together through a rearrangement of design decisions (Continue 3)*

| Decision of Design Specification | | | stage | 64 | 65 | 67 | 21 | 22 | 23 | 46 | 18 | 19 | 42 | 47 | 54 | 55 | 66 | 56 | 17 | 63 | 36 | 38 | 39 | 40 | 41 | 53 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 5 | Frame | ergonomic factor | 2 | | | | | | | | | | | | | | | | | | | | | | | |
| 25 | Frame | Homologation | 3 | | | | | | | | | | | | | | | | | | | | | | | |
| 48 | Frame | Type of fabricate machine (part production) | 7 | | | | | | | | | | | | | | | | | | | | | | | |
| 9 | Frame | Product durability | all | | | | | | | | | | | | | | | | | | | | | | | |
| 1 | Frame | Material type | 2 | | | | | | | | | | | | | | | | | | | | | | | |
| 2 | Frame | Product Shape | 2 | | | | | | | | | | | | | | | | | | | | | | | |
| 8 | Frame | Legislation | 2 | | | | | | | | | | | | | | | | | | | | | | | |
| 24 | Frame | Crash safety | 3 | | | | | | | | | | | | | | | | | | | | | | | |
| 50 | Frame | Source of production process/machine/tool | 7 | | | | | | | | | | | | | | | | | | | | | | | |
| 7 | Frame | Additional function of seat (power seat, heater, etc.) | 2 | | | | | | | | | | | | | | | | | | | | | | | |
| 6 | Frame | key function of seat (e.g. foldable, lever,etc.) | 2 | | | | | | | | | | | | | | | | | | | | | | | |
| 31 | Frame | maintenance factor | 4 | | | | | | | | | | | | | | | | | | | | | | | |
| 4 | Frame | Appearance of product | 2 | | | | | | | | | | | | | | | | | | | | | | | |
| 32 | Frame | Productivity | 4 | | | | | | | | | | | | | | | | | | | | | | | |
| 30 | Frame | environmental factor (e.g. Noise and vibration) | 4 | | | | | | | | | | | | | | | | | | | | | | | |
| 29 | Frame | Product safety (e.g. Robustness) | 4 | | | | | | | | | | | | | | | | | | | | | | | |
| 3 | Frame | Product size | 2 | | | | | | | | | | | | | | | | | | | | | | | |
| 49 | Frame | Type of Assembly machine (part production) | 7 | | | | | | | | | | | | | | | | | | | | | | | |
| 57 | Frame | Detail specification of fabricating machine (part production) | 8 | | | | | | | | | | | | | | | | | | | | | | | |
| 28 | Frame | The setting of tolerance and standard of product | 4 | | | | | | | | | | | | | | | | | | | | | | | |
| 14 | Pad foam | Legislation | 2 | | | | | | | | | | | | | | | | | | | | | | | |
| 10 | Pad foam | Product Shape | 2 | | | | | | | | | | | | | | | | | | | | | | | |
| 11 | Pad foam | Product size | 2 | | | | | | | | | | | | | | | | | | | | | | | |
| 12 | Pad foam | Appearance of product | 2 | | | | | | | | | | | | | | | | | | | | | | | |
| 37 | Pad foam | Productivity | 4 | | | | | | | | | | | | | | | | | | | | | | | |
| 52 | Pad foam | Type of fabricate machine (part production) | 7 | | | | | | | | | | | | | | | | | | | | | | | |
| 45 | Pad foam | Source of production process/machine/tool | 6 | | | | | | | | | | | | | | | | | | | | | | | |
| 61 | Pad foam | Detail specification of fabricating machine (part production) | 8 | | | | | | | | | | | | | | | | | | | | | | | |
| 13 | Pad foam | ergonomic factor | 2 | | | | | | | | | | | | | | | | | | | | | | | |
| 16 | Pad foam | Product durability | all | | | | | | | | | | | | | | | | | | | | | | | |
| 15 | Pad foam | Homologation | 2 | | | | | | | | | | | | | | | | | | | | | | | |
| 26 | Pad foam | Material type | 3 | | | | | | | | | | | | | | | | | | | | | | | |
| 43 | Frame | Source of material | 6 | | | | | | | | | | | | | | | | | | | | | | | |
| 44 | Pad foam | Source of material | 6 | | | | | | | | | | | | | | | | | | | | | | | |
| 62 | Pad foam | Material flow (transportation from-to supplier and customer) | 8 | | | | | | | | | | | | | | | | | | | | | | | |
| 58 | Frame | Detail specification of Assembly machine (part production) | 8 | | | | | | | | | | | | | | | | | | | | | | | |
| 59 | Frame | Material flow (transportation from-to supplier and customer) | 8 | | | | | | | | | | | | | | | | | | | | | | | |
| 60 | Frame | Production process standard and tolerance | 8 | | | | | | | | | | | | | | | | | | | | | | | |
| 51 | Frame | Production and assembly flow (step of production) | 7 | | | | | | | | | | | | | | | | | | | | | | | |
| 27 | Pad foam | Crash safety | 3 | | | | | | | | | | | | | | | | | | | | | | | |
| 33 | Pad foam | The setting of tolerance and standard of product | 4 | | | | | | | | | | | | | | | | | | | | | | | |
| 34 | Pad foam | Product safety (e.g. Robustness) | 4 | | | | | | | | | | | | | | | | | | | | | | | |
| 35 | Pad foam | environmental factor (e.g. Noise and vibration) | 4 | | | | | | | | | | | | | | | | | | | | | | | |
| 20 | Trim coverin | Appearance of product | 2 | 2 | 2 | 2 | | | | 2 | x | x | | 2 | 2 | 2 | | | x | | | | | | | |
| 64 | Trim coverin | Detail specification of fabricating machine (part production) | 8 | ■ | | | | | | x | x | x | | x | x | | | | x | | | | | | | |
| 65 | Trim coverin | Detail specification of Assembly machine (part production) | 8 | | ■ | | | | | x | x | x | | x | | x | | | x | | | | | | | |
| 67 | Trim coverin | Production process standard and tolerance | 8 | | | ■ | | | | | x | x | | | x | x | | | x | | | | | | | |
| 21 | Trim coverin | Legislation | 2 | 2 | 2 | 2 | ■ | | x | | | x | | 2 | 2 | 2 | | | x | | | | | | | |
| 22 | Trim coverin | Homologation | 2 | | | 2 | x | ■ | x | | | | | | | | | | | | | | | | | |
| 23 | Trim coverin | Product durability | all | 2 | 2 | 2 | x | x | ■ | 2 | | | | | 2 | 2 | | | | | | | | | | |
| 46 | Trim coverin | Source of material | 6 | | | | | | | ■ | | | | | | | | | x | | | | | | | |
| 18 | Trim coverin | Product Shape | 2 | 2 | 2 | 2 | x | | | | ■ | | | 2 | | | | | x | | | | | | | |
| 19 | Trim coverin | Product size | 2 | 2 | 2 | 2 | x | | | | x | ■ | | 2 | | | | | | | | | | | | |
| 42 | Trim coverin | Productivity | 4 | 2 | 2 | 2 | | | | | x | x | ■ | 2 | 2 | 2 | 2 | 2 | x | | | | | | | |
| 47 | Trim coverin | Source of production process/machine/tool | 6 | | | | | | | | x | x | x | ■ | | | | | x | | | | | | | |
| 54 | Trim coverin | Type of fabricate machine (part production) | 7 | | | | | | | | x | x | x | | ■ | | | | x | | | x | | | | |
| 55 | Trim coverin | Type of Assembly machine (part production) | 7 | | | | | | | | x | x | x | | | ■ | | | x | | | x | | | | |
| 66 | Trim coverin | Material flow (transportation from-to supplier and customer) | 8 | | | | | | | x | | | | x | x | x | ■ | | | | | | | | | |
| 56 | Trim coverin | Production and assembly flow (step of production) | 7 | | | | | | | x | | | x | x | x | x | x | ■ | | | | | | | | |
| 17 | Trim coverin | Material type | 2 | 2 | 2 | 2 | x | | | 2 | | | | 2 | 2 | 2 | 2 | 2 | ■ | | | | | | | |
| 63 | Pad foam | Production process standard and tolerance | 8 | | | | | | | | | | | | | | | | | ■ | x | | | | | |
| 36 | Pad foam | maintenance factor | 4 | | | | | | | | | | | | | | | | | | ■ | | | | | |
| 38 | Trim coverin | The setting of tolerance and standard of product | 4 | 2 | 2 | 2 | | | | | x | x | | 2 | 2 | 2 | | | x | | | ■ | | | | |
| 39 | Trim coverin | Product safety | 4 | 2 | 2 | 2 | x | | | 2 | | | | | | 2 | | | | | | | ■ | | | |
| 40 | Trim coverin | environmental factor (e.g. Noise and vibration, cleanliness) | 4 | 2 | 2 | 2 | | | x | 2 | | | | | 2 | 2 | | 2 | x | | | | | ■ | | |
| 41 | Trim coverin | maintenance factor | 4 | 2 | 2 | 2 | | | | 2 | | | | | | | | | x | | | | | | ■ | |
| 53 | Pad foam | Production and assembly flow (step of production) | 7 | | | | | | | | | | | | | | | | | | | | | | | ■ |

## 11.5 SUMMARY OF FINDING FROM THE CASE STUDIES

The two different case studies aim to refine the framework applicability and to demonstrate the implementation of this framework with simple and complex products. For these purposes, this section therefore concludes the refinements and benefits of the framework from the implementation of each case study. Furthermore, the key factors affected the framework performance are also summarised to support the implementation of manufacturing companies.

### *11.5.1 Conclusions of findings from Case Study 1*

The first case study was demonstrated the framework application with a small design and manufacturing business. Based on the substantial amount of information, the assessment methods within the framework phase one were systematically measured the frequency of design update of different products, assessed resource consumptions of their production system. Therefore, three product types and seven production processes which were feasible to gain benefit from a Co-design process adoption.

In the context of design practice, the design activities in the company were managed by the informal design processes. The design specifications were mainly subjected to a customer requirement and/or a decision of a single designer. Hence, PS designers barely have authority on the PS decision because PS design has only a few design changes and mainly resulted from product design decisions. Under this situation, the implementation of the second phase, especially the modelling design process, was rather difficult since a designer was a shortage of knowledge related a concept of a formal design process. However, this has shown the usefulness of the design decision allocation checklists in which a designer was able to utilise the design decision allocation checklist to form the formal design process. In addition, a designer also had difficulty during applying ecological identification, particularly for a product design format, because the provided criteria (a type of resources, i.e. material, energy and water) was more presented in the context of PS aspect. This therefore supported the refinement of criteria to be more understandable and applicable by a product designer. Apart from these, the developed design processes assessment approaches were able to identify co-design specification with the suggestion of the suitable method for co-design adoption.

In summary, a company X has visualised how the simultaneous consideration of product and production system design should be applied in order to improve the resource efficiency of their production system through the application of P&PS Co-design framework. It is however the application of a new co-design process is currently impossible due to the lack of basic design knowledge, the required improvement of information related to resource consumption and the empirical study of a new co-design process implementation, the designers, have recognised the resource-efficient benefit of equal consideration of product and production system specification. Besides, regarding the suggestion provided as the output of the case study, the senior designer will consider improving designers' basic knowledge related to a formal design process and sustainability. the company in which this could consider as the initiation of design process improvement and enhance readiness for adopting P&PS Co-design process in future.

### *11.5.2 Conclusions of findings from Case study 2*

The second case study has demonstrated the framework application to the complex design product of large manufacturing companies. Even though the part of information (related production system) was not available due to the confidential nature of the data, the implementation of the first phase was effectively conducted using the provided design data from a collaborated company and the production system data from the literature. In detail, the assessment methods within the first phase systematically measured a frequency of seat design update, assessed resource consumptions of the seat production systems. As a result, the identified seat designs and their seven production processes which were potentially be improved by a Co-design process adoption.

The assessment at the second phase mainly focused on design processes. In this case, the design activities in this company were managed by the formal and well-structured complex design processes. The collaborated seat design engineers were familiar with the well-structured design processes, design organisation and design management. Therefore, the implementation of the second phase of the framework was successfully applied due to the maturity of the design organisation and design knowledge. The usefulness of the developed methods within this second phase was presented through this case study. Nonetheless, in addition to the provided design decision allocation checklists, seat design engineers informed the additional information related to design specification, design position and design organisations to support the realisation of seat design and development processes. The table therefore should be able to make a record about a person-in-charge, specifically for the complex approach because of a variety of related design staffs. Thus, the developed design processes assessment approaches were able to identify co-design specification with the suggestion of the suitable method for co-design at distributed design, distributed control organisation.

In summary, the developed complex design framework approach was supported design engineers to visualise how the potential benefit of resource efficient application can be realised through the identification of the collaborative P&PS design decisions and the adoption of a combined Co-design process. This also provides the support to realise the resource-efficient benefit with a detailed implementation guide. However, this case study has underlined that it is a significant challenge if the automotive company is willing to replace the present seat design and development process with a new co-design process due to the complexity of design organisation (both internal and external automotive company) and the complication related information sensitivity. The companies were encouraged to improve P&PS information exchange, staffs' knowledge (related SD, RE and P&PS design), collaboration between (internal and external) P&PS design organisations and design processes gradually. These improvements could be conducted through the application of the co-create strategy which will be further refined through an empirical study in the future research. Based on this output of the framework application, the engineering design manager realised the potential benefit of this proposed P&PS co-design approach and was aware of the concurrent designs of product and production system. Moreover, he has also suggested that the defined strategies within the Co-create phase will be useful to support the improvement of collaboration between design department (for both low and high experienced designer) and to initiate the new co-design process. This framework could be proposed as the countermeasure idea to improve the collaboration between P&PS design departments if the benefit of a trial implementation is presented.

### *11.5.3 Conclusions of findings from Case studies*

The two case studies have demonstrated the applicability and facilitated the refinement of the developed P&PS Co-design framework for the simple and complex product. Within these two different case studies, three factors which are design practice, collaboration and agreement on the Co-design objective, and availability and accessibility of information were denoted as the key factors supporting the successful implementation of the simple and complex design framework approach.

#### *11.5.3.1 Design practice*

The current design practice in a company directly impacted on the effectiveness of the application of the framework in both steps of the design process assessment and a co-design process adoption. Without the implementation of a formal design process, a designer was unable to visualise and understand the need to improve design practices. Hence, a designer had the difficulty to implement the design processes assessment. In contrast, the implementation of the framework was effectively conducted with the support from various designers working under a formal design process. This also highlighted that, where the informal design process was used, PD and PSD designers need to understand a basic design knowledge related to their current work before providing further knowledge related P&PS design.

#### *11.5.3.2 Collaboration and agreement on the Co-design objective*

There is a challenge in applying any changes within an organisation. In this case, the implementation of P&PS co-design framework directly results at the change of design practice. Therefore, based on the case studies, one of the critical challenges is collaboration. The collaboration was needed to support during both the assessment phases and the Co-design creation phase. At the assessment application, the effective collaboration was requested to collect all necessary data in which it was found that the successful collaboration could be built on the agreement on the objective of the project. For the process creation, strengthening design collaboration seems to be manageable for a company that has the simple design process. This is because the small number of related persons worked in a central design and central control organisation. While, at the complex design process structure, a complex product was designed by various design teams from a single company or multiple companies. In this case, the creation of the co-design process is very challenging, especially to strengthen the collaboration within an organisation and across the supply chain.

#### *11.5.3.3 Availability and accessibility of information*

The availability and accessibility of information were affected by the success of the framework implementation. The decision related the investment and improvement of the new design process required a correct result of the assessments which critically depended on the availability and accessibility of information. Based on the case studies, it appeared that the unavailability of information was likely to occur at a small company due to a lack of well-organised design practice.

While, at a large company, the information was documented and available, but inaccessible due to the data confidential issue. Consequently, this factor is substantially affected by the successfulness of the framework implementation. Particularly where the complex design processes were applied, this factor could be a considerable challenge to enable information exchange between design teams, design sections, particular between different companies.

## 11.6 CHAPTER SUMMARY

This chapter reported two case studies applied in this research to validate and refine the P&PS Co-design framework. The first case study demonstrated the simple design framework approach to support a packaging design and manufacturing company, which frequently update the design of the product but have a small change in a production system. This company therefore was able to visualise the benefit of co-design adoption, to improve their design practice and to adopt co-design through an insignificant change of the design process. For the second case study, with the supported from an automotive company, the complex design framework approach was demonstrated through the automotive seat design and the seat manufacturing chain where designs of the seat and its production system were often updated. These case study demonstrated the effective implementation of the proposed complex approaches and enable the ability to visualise and gain the benefit of co-design adoption through gradual changes of design practice.

In sum, these case studies have shown how the developed framework was able to support the different manufacturers to identify the benefit of co-design and transform the existing design processes into a single co-design. The findings of the case studies are very useful in the refinement of the applicability of the developed methods within this framework.

# CHAPTER 12 CONCLUDING DISCUSSIONS

## 12.1 INTRODUCTION

This chapter summarises the main research contributions and identifies the new knowledge and key findings generated by the research. The main sections of the chapter discuss the overall achievements of the research in line with defined objectives as well as any limitations of work undertaken.

## 12.2 RESEARCH CONTRIBUTIONS

In the areas of integrated design, sustainable design and resource efficient manufacturing, the fundamental contributions of this research have been as follows:

i. Introduction of a new approach that builds upon the existing ID approaches which focus on the integration between two independent P&PS design processes through information sharing and exchange, by defining and implementing a single concurrent P&PS co-design process to cope with the increasing complications in design, especially those related to resource efficiency considerations.
ii. Development of the P&PS co-design framework to enable the ability to visualise the interrelations between product and production system design activities based on the resource-efficient consideration through the identification of the potential resource-efficient benefits, the specification of design decisions and the establishment of a collaborative design process.
iii. Generation of a new method to identify the potential benefits of implementing a collaborative design process through the quantitative measurement of the frequency of design updates and level of resource consumption by production processes.
iv. Creation of a novel method to specify the design decisions which impact on the resource consumption of the production system by considering the environmental factors such as energy, water consumption and material waste generated.
v. Definition of the three strategies to support the implementation of a new single co-design process for manufacturing companies with varying design complexities and requirements.

This also includes a long-term plan, implementation guide, and an additional evaluation method supporting collaboration improvement between design processes.

vi. Development of the P&PS Co-design prototype software tool using Microsoft Excel and Visual Basic Programming Language to support and demonstrate the implementation of the proposed framework.

vii. Demonstration of the applicability of the proposed framework through industry-based case studies, highlighting the potential for improvement in resource efficiency.

## 12.3 CONCLUDING DISCUSSIONS

Based on the research scope outlined in chapter 2, the major results from various research activities are summarised in the following subsections.

### *12.3.1 Review of the state-of-the-art and current practice in the design of the product and production system*

As a foundation for this research, a review of the state-of-the-art in independent and integrated design approaches to product and production system design was undertaken to understand the basic knowledge, to explore the design evolution and to identify current gaps in ID concepts. This review covered the literature related the existing concepts, approaches, methods, tools and current practices as well as the recent shortcomings reported in PD, PSD and ID. The literature published under independent design processes provides a basic design knowledge but lacks clear guidelines supporting design integration between P&PS. Significantly, a need for new approaches which include considerations of contemporary requirements such as the critical environmental issues (e.g. resource efficiency), changeability and interdisciplinary collaboration has also been highlighted by many publications in this subject area.

The review of the existing integrated design concepts highlighted that majority of these were originated, developed and applied to achieve the traditional and narrow targets such as improving development time, improving manufacturability and reducing cost. Moreover, most of the studies focused mainly at an enhancement of overlapped processes, cross-functional teams and information sharing, without wider considerations for long-term objectives such as improving the resource efficiency. For these reasons, such approaches are widely adopted in academia but not for industrial applications. In fact, the adoption of integrated design approaches has been declining, owing to the failure of any significant observed benefits. It has been found that the improper implementation without a structured approach, inaccessibility of information, and inability to manage complex processes are the main causes of unsuccessful ID applications. In response, several researchers have highlighted that ID approaches should be organised under the formal and structured design processes and initiated with a clear objective and mission, and they should be upgraded to promote a more interdisciplinary, collaborative and concurrent approach to design.

### *12.3.2 The need for a single P&PS co-design process*

The ever-increasing range of complexities and demands on design processes for P&PS necessitates a more flexible and responsive approach to undertaking various design activities. As stated, the traditional ID approaches, which were originated to achieve specific targets such as reduction of development time and cost, are too rigid to for the unavoidable needs of sustainability applications. In addition, the current application of ID approach has mainly supported a unidirectional information sharing (i.e. from product to production system design). Hence, there is a need to transform the present integration practices towards a single co-design process which support bi-directional collaborative design activities.

The need to consider sustainability considerations during design is another driver for the development of a more collaborative multidisciplinary approach to the design of P&PS. In particular, in the context of resource efficiency, the current shortcomings are associated with lack of simple guidance, late consideration of these issues during design processes, inability to instantly assess the effect of change between designs of P&PS, absence of multidisciplinary knowledge and a shortage of methods to consider the trade-off among multiple resources (e.g. energy versus water consumption). This highlight a need for a new sustainable design solution for P&PS in which any potential benefits could be readily and seamlessly assessed during the early stage of design processes.

### *12.3.3 A framework for co-designing product and production system to support resource-efficient manufacturing*

This research has highlighted the need to implement a single co-design process in response to the increasing design requirements especially those related to conserving natural resources. Although this single process has been promoted as an approach with many potential benefits, it is also accepted that not every manufacturer will benefit from its adoption. This is because each product type requires different design focus on resource efficiency, possesses varying interrelationships between its key design decisions, and is updated with different frequency. To provide a structured approach for assessing the suitability of co-design as well as guidelines for its implementation, the P&PS Co-design framework which comprises of four phases has been developed. The first phase provided the method to determine whether a company can gain any benefits from the adoption of a new co-design process, before committing further efforts and investments. If the adoption of the co-design process is assessed to be beneficial, then the current separated design processes of P&PS are decomposed to identify the co-design decisions through the ecological interrelation assessment in the second phase. Similarly, based on the results of the previous two phases, the third phase offers the three possible strategies for supporting creation and implementation of a new single P&PS process for companies with varying size, type and capabilities. These strategies could also be used by a company as the gradual step-wise transition from its current independent P&PS design processes to a single co-design process. Finally, the fourth phase of the framework is supported through development of a software toolkit to underpin the implementation of P&PS co-design process.

### *12.3.4 Strategies for creation and implementation of a single co-design process*

Due to various design requirements related to different product types, every manufacturer will need to adopt a different approach to the implementation of the co-design process to achieve resource-efficient manufacturing. This research has utilised the four key characteristics of integrated design (see Section 3.4.1) to develop three optional strategies to support a range of design and manufacturing scenarios.

In a case where the interrelations between product and production system design is low, this P&PS co-design can be performed through the 'Awareness' strategy. Through this first strategy, a company can operate P&PS co-design through an improved knowledge and information exchange. Designers may need to be reskilled to gain a wider knowledge of product, production process and sustainability, and information systems must be improved to unlock the accessibility of information between product and production system designers.

Secondly, the 'Association' strategy is developed to support a co-design creation in cases where the interrelation between product and production system designs are relatively complex. In this strategy, only a partial transformation of a subset of the independent P&PS design processes into a single co-design process is recommended.  Finally, the 'Adaptation' strategy was defined to support a company where the interrelation between P&PS design is critically high because of the number of interdependencies between many co-design decisions within the design processes. Through this strategy, reskilling of designers are required to implement a new single co-design process.

Any changes to a design process represent a significant challenge, in particular, in the case of Adaptation strategy which necessitates changes in design practices (i.e. collaboration procedure and design process), facilities (i.e. information sharing system) and resources (i.e. designers' skills). Thus, the creation of a single co-design process should be considered as a long-term mission and managed through gradual changes.

### *12.3.5 Development of a toolkit supporting the P&PS Co-design framework implementation*

The range of assessments and analysis included in the P&PS Co-design framework requires a significant amount of data to be collected, processed and presented to different users. Therefore, this research has developed the P&PS Co-design prototype software tool to support and simplify the application of the various steps within this framework. The tools consist of a number of specially designed screens to collect relevant information from both product and production system designers. This data is then processed by the PPC tool, using the functional relationships and equations outlined in Chapters 8 and 9. Finally, the results in the form of specially designed tables, charts and statement are presented to users. Where possible, a number of related results from analysis and assessments are presented side-by-side in the form of a result sheet (or a dashboard) to aid with decision making (see Figure 10.16). While this prototype tool could effectively assist the application of P&PS framework, its application for commercial use requires significant upgrading and improvements, e.g. improvement of data collection to the realisation of the actual design process in practice. Finally, the PPC tool could be used in conjunction with several commercial and/or research tools to improve its overall functionality, as outlined in Chapter 10.

### *12.3.6 Demonstration of the applicability of the P&PS Co-design framework through case studies*

Two case studies were conducted to demonstrate the implementation of the proposed P&PS Co-design framework. These represent examples of a simple and a complex product.

The first case study was applied to a small-medium enterprise which produced a wide range of packaging products that are frequently updated. The application of the first phase P&PS co-design framework helped the company to identify the three types of products and seven production processes which potentially gained benefit from the adoption of a co-design process. During the second phase, the difficulties of company staff to use the modelling design tables assisted the author to improve the design of these tables. Moreover, this also highlighted that a practical and successful application of the framework is based on the availability of relevant data related to the formal design processes, the knowledge related to the design of production processes and their resource efficiency, and the common understanding of co-design objective among designers. This case study also resulted in the refinement of the 'Association' strategy throughout the research based on the specific requirements of a small and medium enterprise.

The second case study was conducted in collaboration with a large company which designed and manufactured a more complex product (i.e. automotive seat). Due to time constraints, the implementation of the framework was limited with a complex sub-assembly of the overall product which is designed jointly with another manufacturing company. Hence, this case study has shown the applicability of the framework, especially during the first two phases, across two different companies. This case study has also underlined the complexity and difficulty in the creation and implementation of a single co-design process within larger companies because of the required large-scale changes of design organisations. These changes included a reskilling of P&PS designers, changes to organisational structures and processes, an investment of a new design tool and the provision of seamless access to relevant knowledge and information across companies. In this case, the close collaboration and the agreement on the co-design objective among design teams were highly significant to the efficient implementation of the framework.

### *12.3.7 Toward a single P&PS Co-design process for supporting resource efficiency*

Designers are facing a higher complication in their day-to-day activities due to the increasing numbers of unavoidable design requirements such as the demand for a higher frequency of product updates, shorter product lifetime and environmental considerations as well as the rapid emergence of advanced technologies. In response, the requirement for further integration between design processes has been commonly reported as one of the most urgent challenges facing the design research community. Therefore, this research has proposed the evolution of current ID between two independent design processes into a single co-design process. Unlike other existing ID concepts such as CE and DfM, P&PS co-design does not simply try to apply PSD considerations as a manufacturability constraint in PD. The P&PS co-design concept aims to improve the effectiveness of complicated design decisions making and facilitate the potential sustainability benefits such as those related to resource efficiency consideration. Therefore, the manufacturer can gain more benefits from early consideration of sustainable design concepts instead of incremental benefits which typically achieved through current ID and SD applications.

As mentioned in the previous sections, many companies might currently not be ready for such radical transformational approach towards a single P&PS co-design process due to reliance to legacy systems, associated efforts and costs, and the level of required reskilling of their designers. In addition to these, a company might encounter many difficulties in attempting to strengthen the collaboration between teams which used to be in conflict due to ineffective redesign management procedures. Hence to ensure long-term success, a company must make a firm commitment to encourage their designers to clearly understand the specific needs and main objectives for the adoption of P&PS Co-design.

Apart from the rapid increase in product updates and environmental challenges, in the near future, manufacturing business must be in the position to track and apply the emerging manufacturing technologies such as new smart materials, process automating an industrial robot. The concepts associated with Industry 4.0, Internet of Things and Big data are all indicative of a requirement for an innovative and well-structured P&PS co-design process. Hence, the earlier a company adopt such P&PS Co-design, the better they can cope with these emerging challenges and opportunities in the future.

## 12.4 LIMITATIONS OF THIS RESEARCH

The concluding discussions and research contributions have underlined the strength of this research and explained how this research had satisfied the aim and objectives identified at the start of this PhD study. Nonetheless, time constraints and data limitation have resulted in several limitations to this research which is briefly described below:

i. Unavailability of relevant data to implement P&PS co-design framework has been identified as one of the main obstacles to its application.
ii. The research has not considered the operational difficulties associated with very complex products that are designed using a distributed structures, such as those designed using V-model (Sheldrick 2015) commonly utilised by automotive and aeronautical sectors. In such applications, developing a single P&PS co-design approach necessitates contributions and

collaboration among a large number of stakeholders who are managed and incentified by different organisations and companies within a product supply chain.

iii. Significant improvement in overall functionality of PPC prototype software tool is required for the commercial application.

iv. Furthermore detail case studies are required to refine and strengthen the application of the proposed P&PS co-design framework. For example, an additional case study should be conducted with a sensitive and complex product, such as a chassis or an engine of aircraft, which is critically restricted by their specific characteristics such as product safety, high risk, high quality and complex standards.

# CHAPTER 13 CONCLUSIONS AND FUTURE WORK

## 13.1 INTRODUCTION

This chapter reports the key conclusions of the research in this thesis. The research conclusions are summarised in the initial section. Then based on these conclusions, the potential areas of the future studies are suggested as the closing section of the thesis.

## 13.2 CONCLUSIONS

The main conclusions drawn from the research are :

i. The initial review of the literature related to product and production system design practices found that although the existing design approaches provide sufficient fundamental knowledge and formal structures to support various design decisions, these suffer from lack of flexibility and responsiveness to deal with design challenges, in particular, those associated with the most efficient use of resources in manufacturing applications. In such cases, the concurrent consideration of influences of key decisions during products and production systems design processes is of paramount importance to ensure potential gains due to one improvement is not cancelled by changes required in the proceeding and/or subsequent activities.

ii. The ever-increasing complexities of product and production system design requirements within contemporary advanced manufacturing applications also demand a new integrated approach to design. In this context, the conventional concepts of integrated design which mainly focus on information sharing and exchange between two independent processes for product and production system design, do not meet the real need for a multidisciplinary, collective and cooperative approach to design.

iii. The transformation from existing independent design processes into a single combined co-design process, as proposed by this research, required a substantial amount of long-term investment in reskilling designers, improving collaboration between newly formed design teams and novel information and knowledge management tools and techniques. Thus, the manufacturing companies need to ensure feasibility, define potential benefits from P&PS

Co-design adoption. Therefore, this research asserts that a P&PS Co-design is more useful in an application with frequently design updates in both products and their associated production systems, and in cases with substantial potentials for improving overall resource (material, water and energy) efficiency.

iv. The first phase of the proposed P&PS co-design framework, namely the Co-initiate, aims to systematically generate the supporting information and knowledge required to justify the adoption of this novel approach. While a wide-ranging consideration (energy, water, material) regarding the current resource efficiency of production processes has been included, lack of data availability may necessitate simplification of these considerations based on the most critical resource within a particular application.

v. The research has recognised that there are numerous differences in existing design processes based on product and/or production requirements in different manufacturing applications as well as company sizes, types and capabilities. In this context, the development of a generic 'one-size-fits-all' approach has been replaced with a more flexible and gradual approach in the second and third phases of P&PS co-design framework (i.e. Co-Specify and Co-create) through the definition of 3A strategies to suit the requirements within various applications.

vi. There are many challenges to realise and implement the P&PS co-design process in practice. In author's viewpoint, the two most significant challenges in driving this novel concept are the readiness/willingness of a manufacturing company to adopt P&PS co-design due to its many potential benefits, and gradual implementation of new knowledge and information sharing software tool that support a collaborative and cooperative approach to design activities, similar to that of the prototype PPC software tool generated by this research.

vii. While there are a wide range of design considerations impacting the resource efficiency such as material selection, product shape and fabricating process has been included in the P&PS co-design framework, the results from the second case study show that there may be other considerations such as product safety and ergonomics that influences the overall resource efficiency. In such cases, these additional considerations need to be added to the interrelationship assessment checklists.

viii. The distinctly different nature of two case studies based on a simple and a complex product highlighted different changes and transformations required to implement a single co-design process. While in the case of simple product design, the focus should be on improvement of knowledge and information flow, in the case of complex products the focus should be on the development of new collaboration activities, reorganising and restructuring design processes, and reskilling of existing product and production system designers.

ix. It is recommended that for the effective implementation of the P&PS co-design framework, an appropriated P&PS Co-design project manager must be appointed. In this context, such project manager should not only have a comprehensive understanding of existing design processes and be familiar with the company's change management procedures but also be supported by a team of internal and external designers, engineers and planners from various stakeholders within a product lifecycle.

## 13.3 FUTURE WORK

Similar to other research activities, this research was undertaken based on the previous discovery by other researchers. In this context, the authors have identified the following extension to the scope of the research reported in the thesis for future researchers in this subject area.

### *13.3.1 A further empirical study investigating the implementation of the co-design process in manufacturing practice*

Due to the time constraints, chapter 11 highlighted the limitations of the conducted case studies. These two case studies were devised to demonstrate the framework implementation and applicability of proposed research concepts. Further empirical case studies based on different products and company sizes/types are required to ensure and highlight the effectiveness of the three recommended strategies. Such case studies may lead in refining the steps included within various phases of P&PS co-design framework.

### *13.3.2 Extension of a range of criteria adopted in a Co-design process*

The utilisation of this P&PS co-design framework enables an ability to assess changes between designs of a product and its production system with the aim to enhance resource efficiency. Thus, this framework has incorporated environmental considerations into the early stages of design processes so that manufacturers and designers could maximise the potential benefits. However, the range of design decision impacting ecological benefits from co-design consideration may have to be extended and, in some cases, tailored to the specific requirement of a product and/or a company. Also, other potential benefits from such a co-design approach such as reduce time-to-market and design costs, improved product customisation, and the inclusion of social considerations in product and production system design could be further explored.

### *13.3.3 Expansion of co-design to engage the consumers, product designers and production system designers*

This research has proposed the P&PS co-design framework to cope with the increasing design challenges such as complexity in designing resource-efficient P&PS. In addition to this, the literature review also discovered that there was also a research opportunity for a holistic co-design when all consumers, designers, engineers, and related stakeholders collaborated to achieve all design requirements and constraints. The collaboration between end users and designer has been widely recognised through a concept of participatory design (or user experience design) which aims at the better fulfilment of the consumer needs which may also lead to improving overall sustainability within manufacturing applications. The inclusion of consumer into the proposed P&PS co-design process is identified by the author as an essential area of expansion for this research.

### *13.3.4 Development of the software tools supporting the operation of a single P&PS co-design process*

The proposed P&PS Co-design framework aims to assist a manufacturing company in identifying various opportunities in improving the resource efficiency of their products and production activities. To effectively realise this objective, designers should be able to visualise, manage and utilise a wide range of P&PS information and knowledge which needs to be collected, documented, and properly presented to meet the requirement of each co-design activity. In response, there is a need for further development of the software tool supporting co-design decision trade-off and co-design concept selection. Such new software capabilities must focus on highlighting the impact of changes between the interdependent P&PS design specification This might be realised by the improvement of the existing CAD software to not only present the detail of product design but also to outline the interrelation of product and its related production specification. Furthermore, current Life Cycle Assessment software is predominantly used to support product design decisions, which highlight a need to extend the scope of their functionality as well as the relevant standard Life Cycle Assessment data to support production process design.

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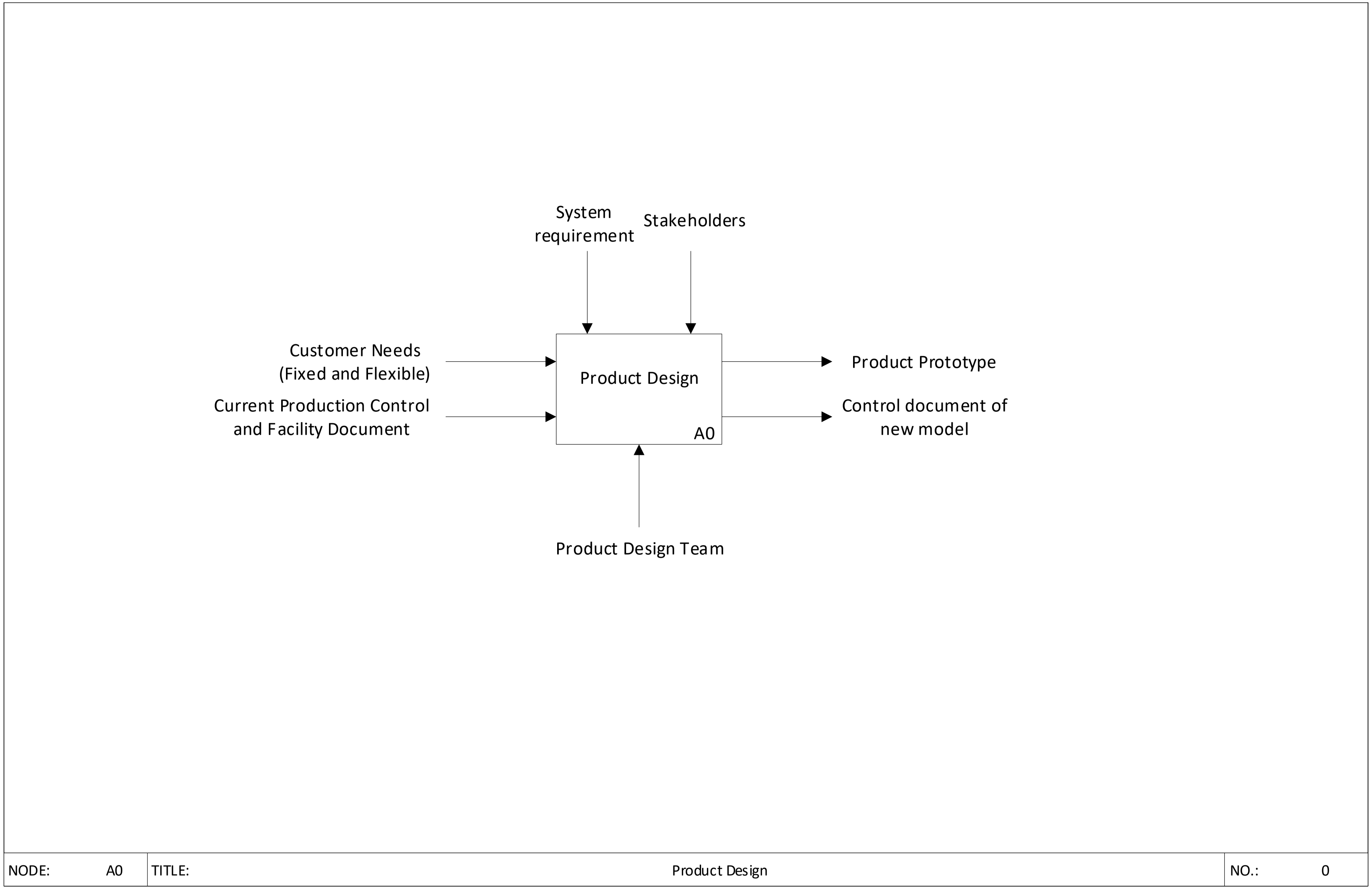
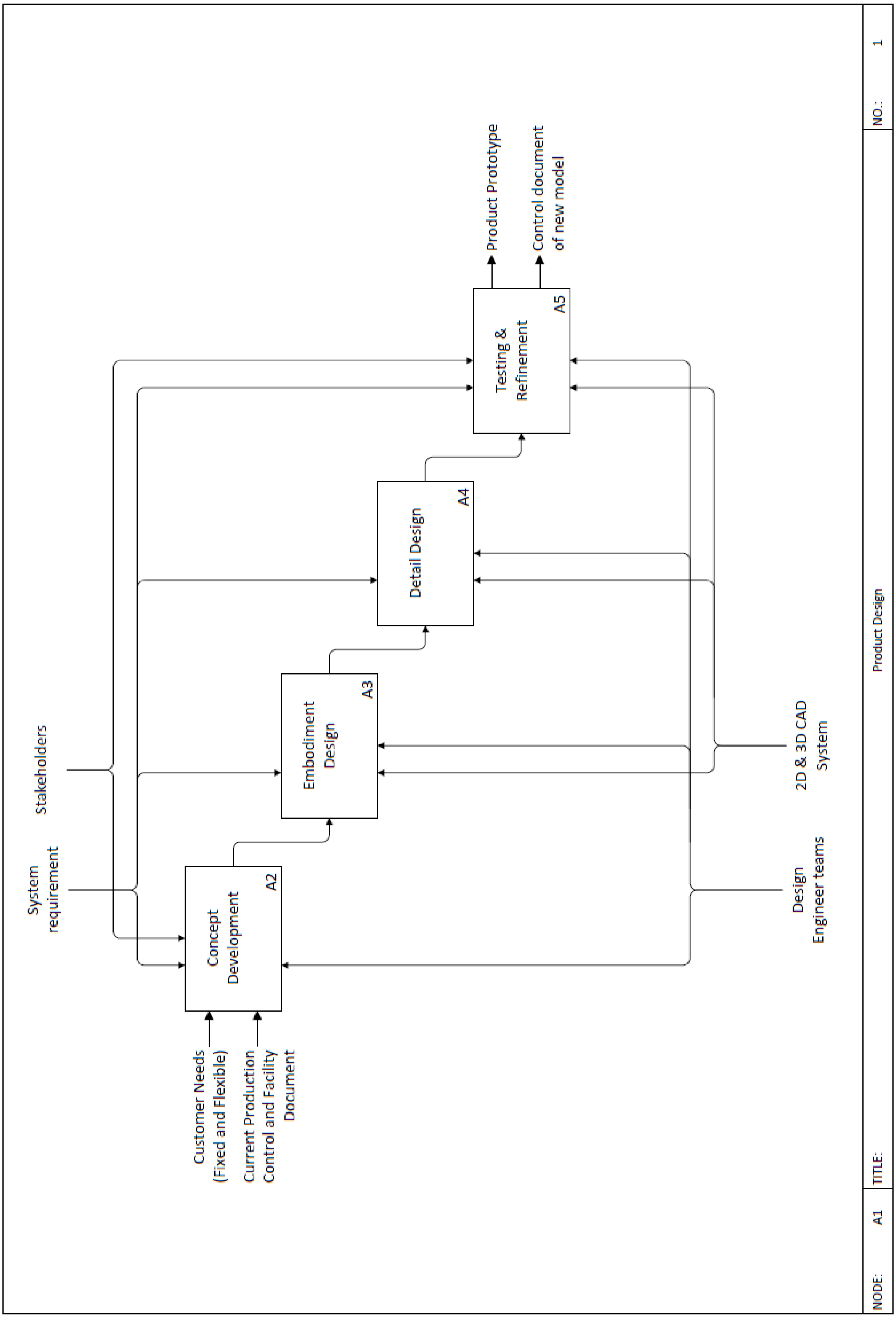
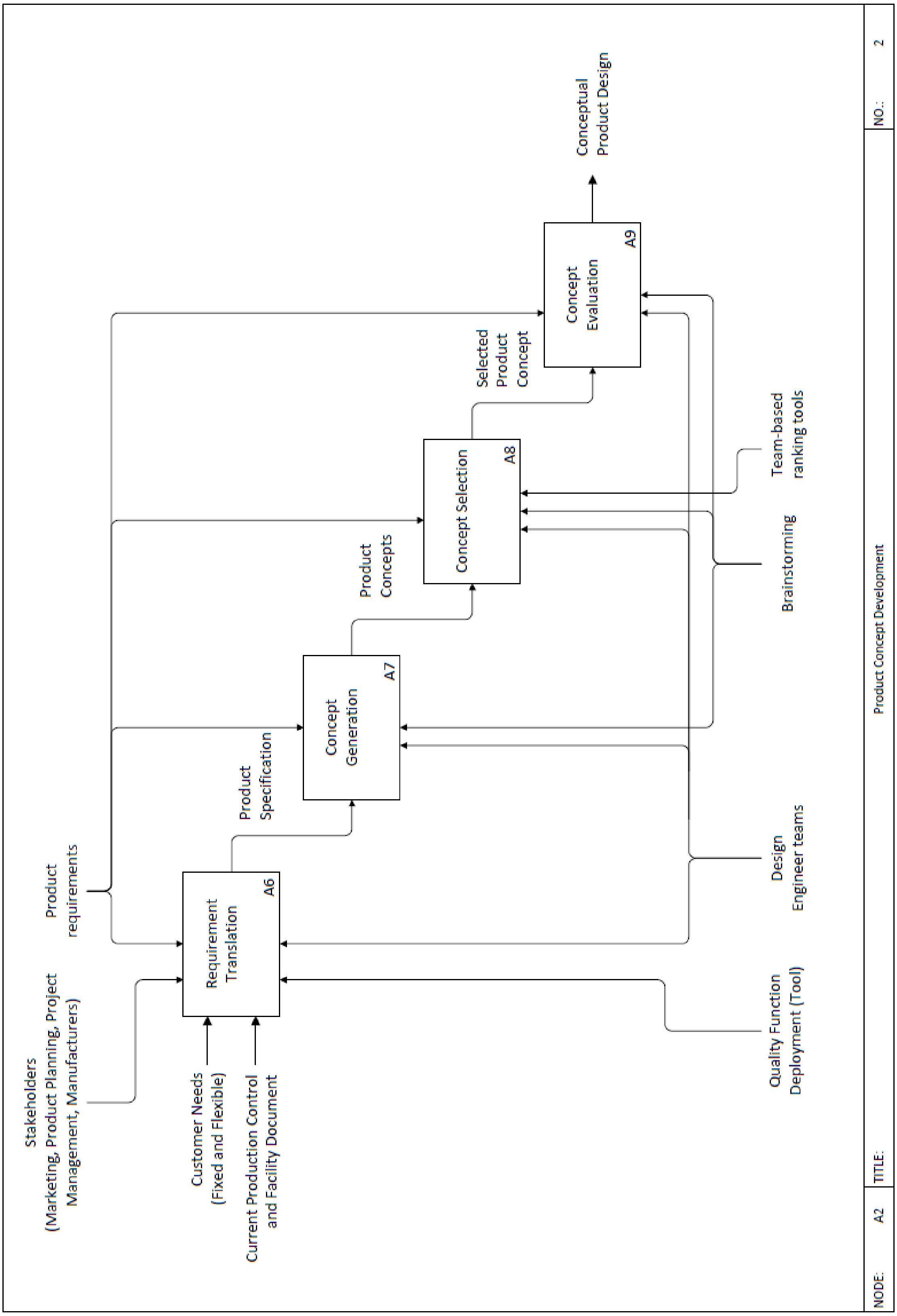
# APPENDIX I IDEF0 OF PRODUCT DESIGN PROCESS

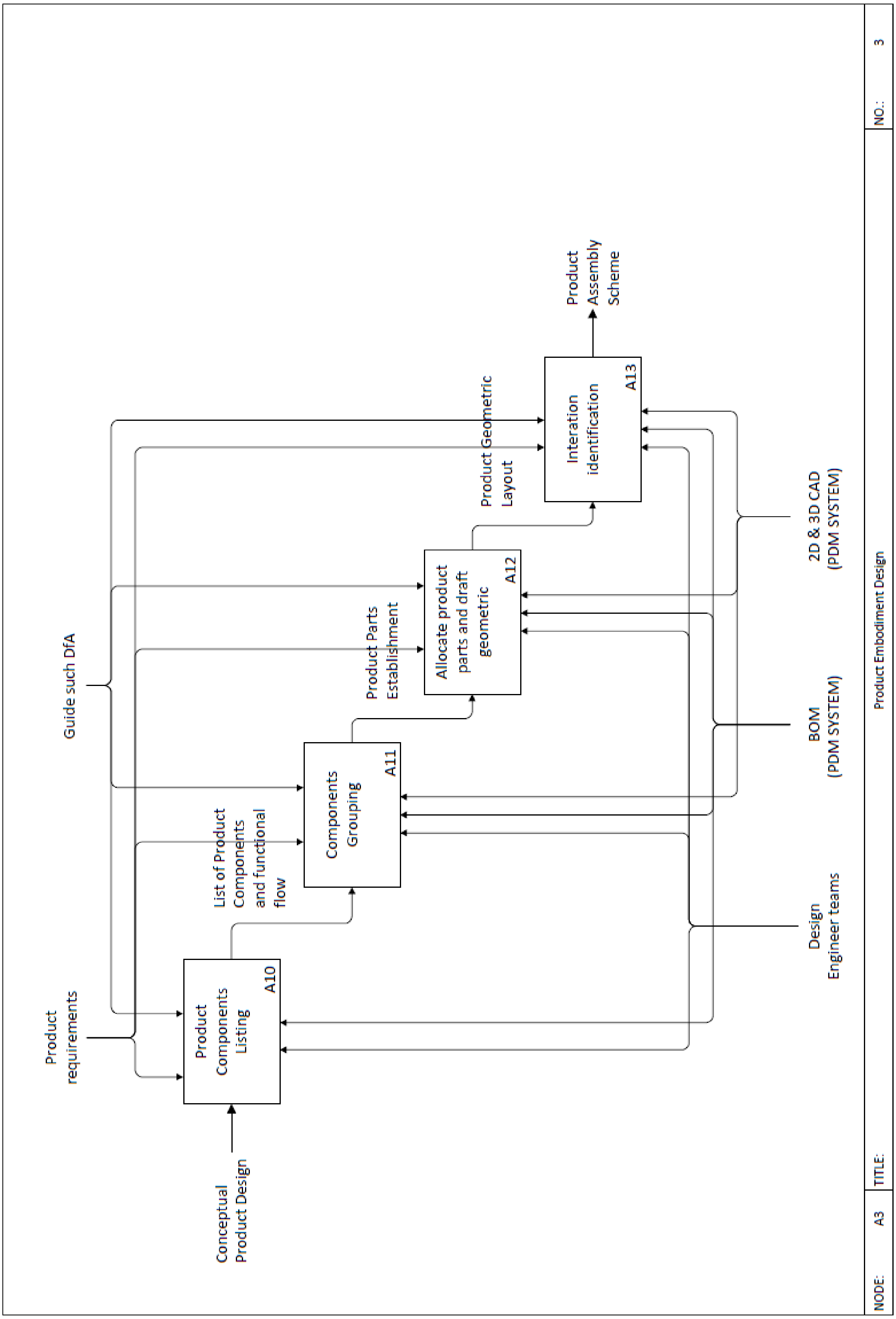
This appendix contains six pages involving three levels of product design process which are:

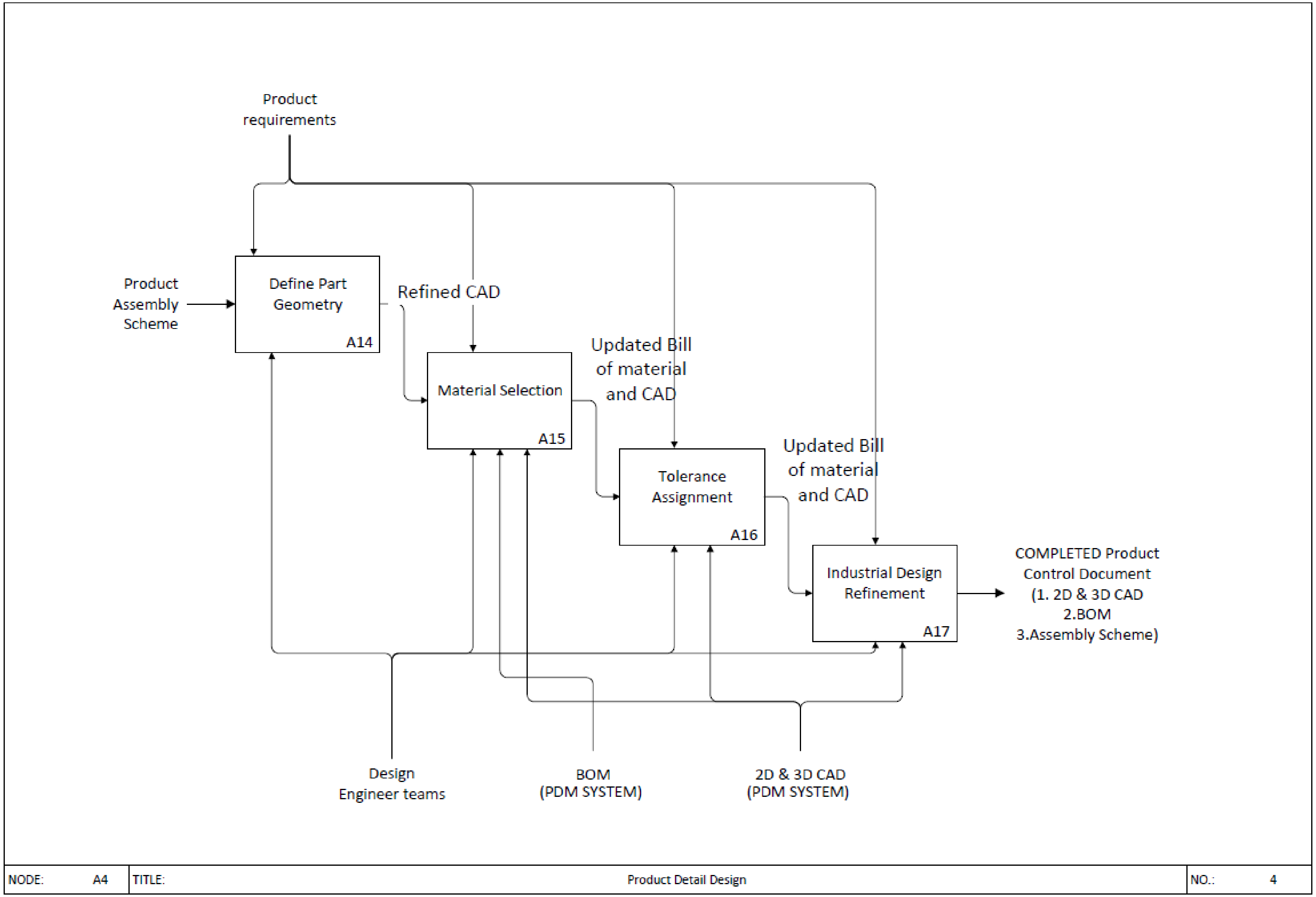
| | |
|---|---|
| Page A2 | Top level of the product design process (Level 1) |
| Page A3 | Four design stages within the product design process (Level 2) |
| Page A4 | Four design steps within the concept development stage (Level 3) |
| Page A5 | Four design steps within the embodiment design stage (Level 3) |
| Page A6 | Four design steps within the detail design stage (Level 3) |
| Page A7 | Four design steps within testing and refinement stage (Level 3) |

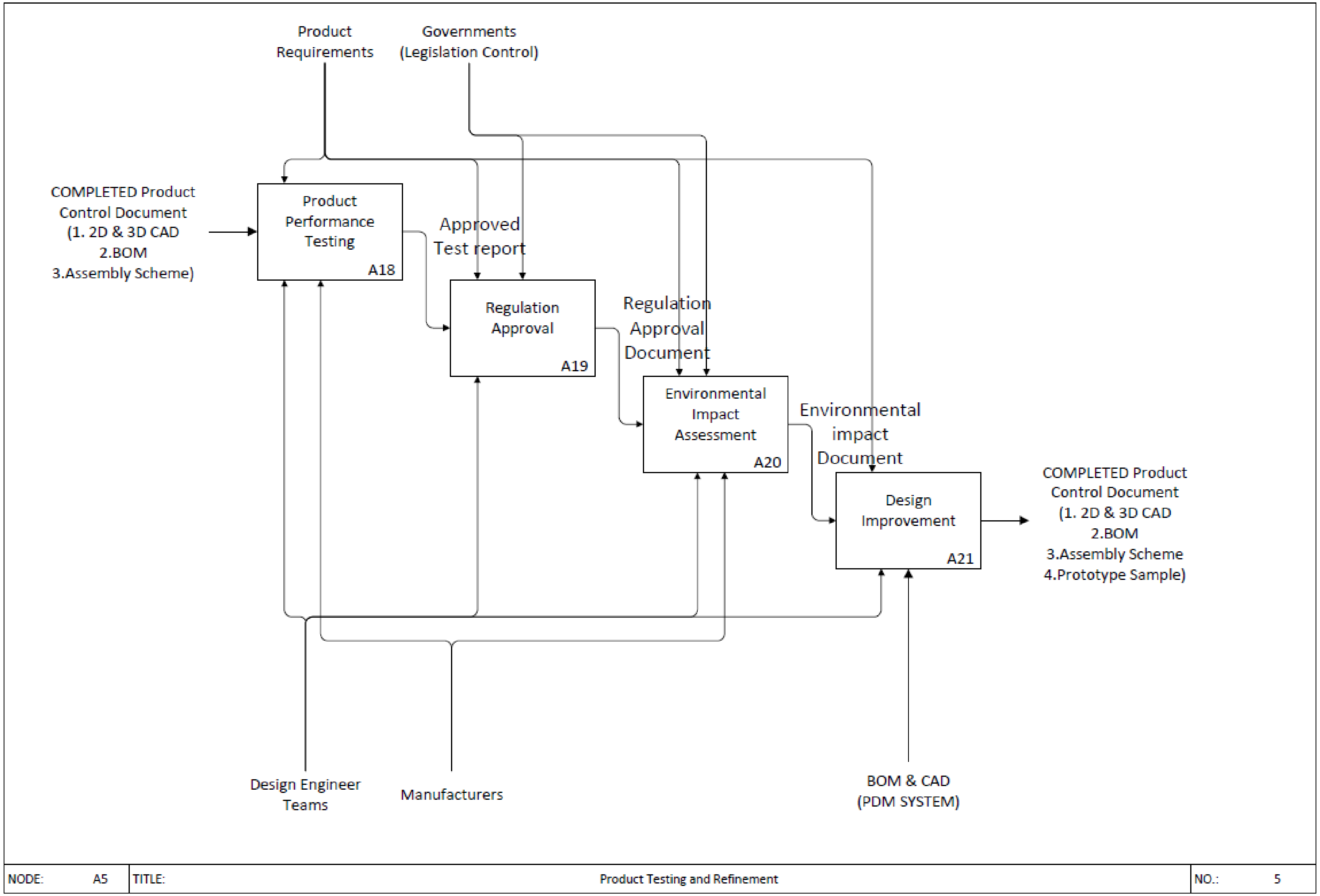

System requirement
Stakeholders
Customer Needs (Fixed and Flexible)
Current Production Control and Facility Document
Product Design
A0
Product Prototype
Control document of new model
Product Design Team
NODE:
A0
TITLE:
Product Design
NO.:
0


Customer Needs (Fixed and Flexible)
Current Production Control and Facility Document
System requirement
Stakeholders
Concept Development
A2
Embodiment Design
A3
Detail Design
A4
Testing & Refinement
A5
Product Prototype
Control document of new model
2D & 3D CAD System
Design Engineer teams
NODE:
A1
TITLE:
Product Design
NO.:
1


Stakeholders
(Marketing, Product Planning, Project Management, Manufacturers)
Product requirements
Customer Needs (Fixed and Flexible)
Current Production Control and Facility Document
Requirement Translation
A6
Product Specification
Concept Generation
A7
Product Concepts
Concept Selection
A8
Selected Product Concept
Concept Evaluation
A9
Conceptual Product Design
Quality Function Deployment (Tool)
Design Engineer teams
Brainstorming
Team-based ranking tools
NODE:
A2
TITLE:
Product Concept Development
NO.:
2


Conceptual Product Design
Product requirements
Guide such DfA
Product Components Listing
A10
List of Product Components and functional flow
Components Grouping
A11
Product Parts Establishment
Allocate product parts and draft geometric
A12
Product Geometric Layout
Interation identification
A13
Product Assembly Scheme
Design Engineer teams
BOM (PDM SYSTEM)
2D & 3D CAD (PDM SYSTEM)
NODE:
A3
TITLE:
Product Embodiment Design
NO.:
3

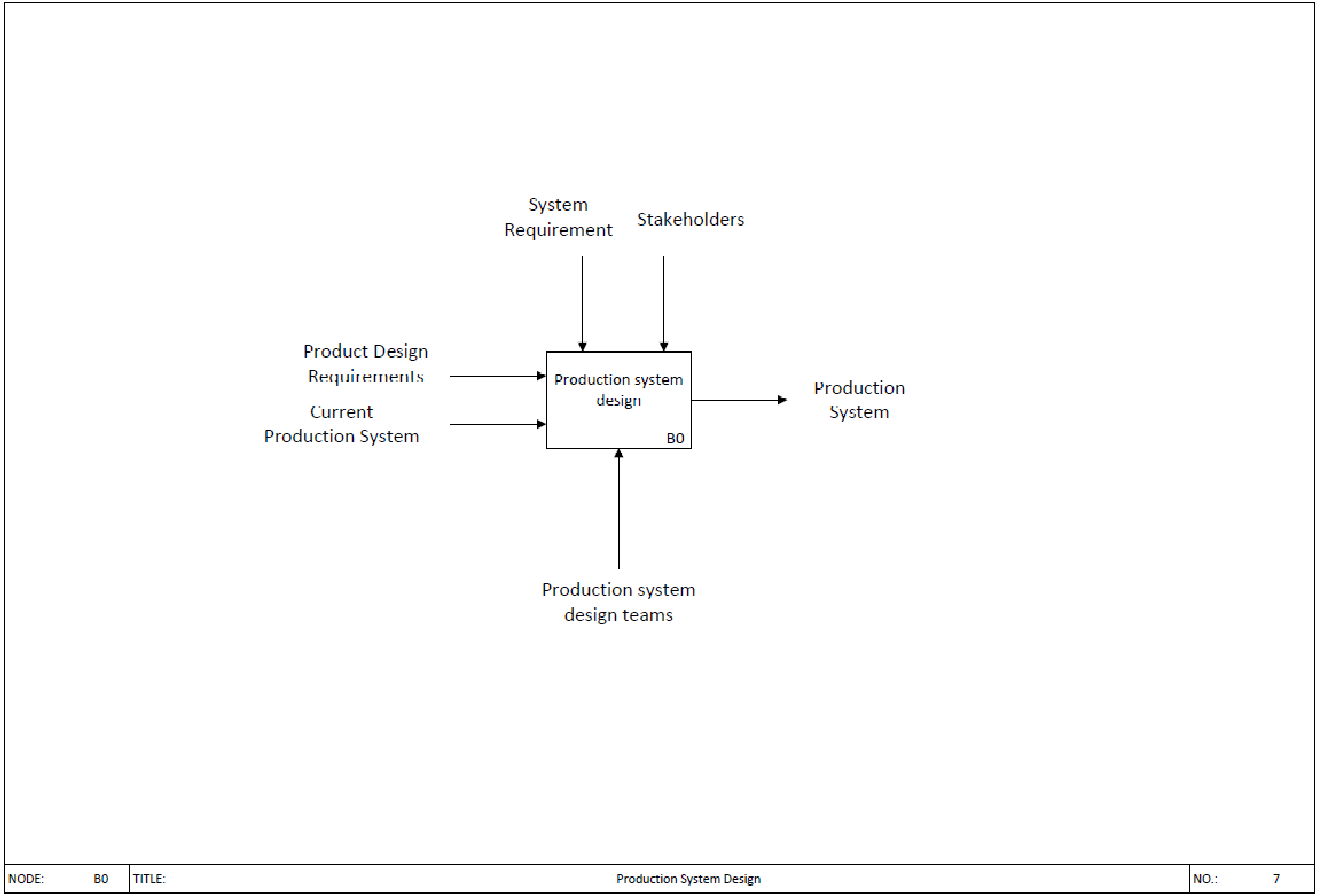

Product requirements
Product Assembly Scheme
Define Part Geometry
A14
Refined CAD
Material Selection
A15
Updated Bill of material and CAD
Tolerance Assignment
A16
Updated Bill of material and CAD
Industrial Design Refinement
A17
COMPLETED Product Control Document (1. 2D & 3D CAD 2.BOM 3.Assembly Scheme)
Design Engineer teams
BOM (PDM SYSTEM)
2D & 3D CAD (PDM SYSTEM)
NODE: A4
TITLE: Product Detail Design
NO.: 4

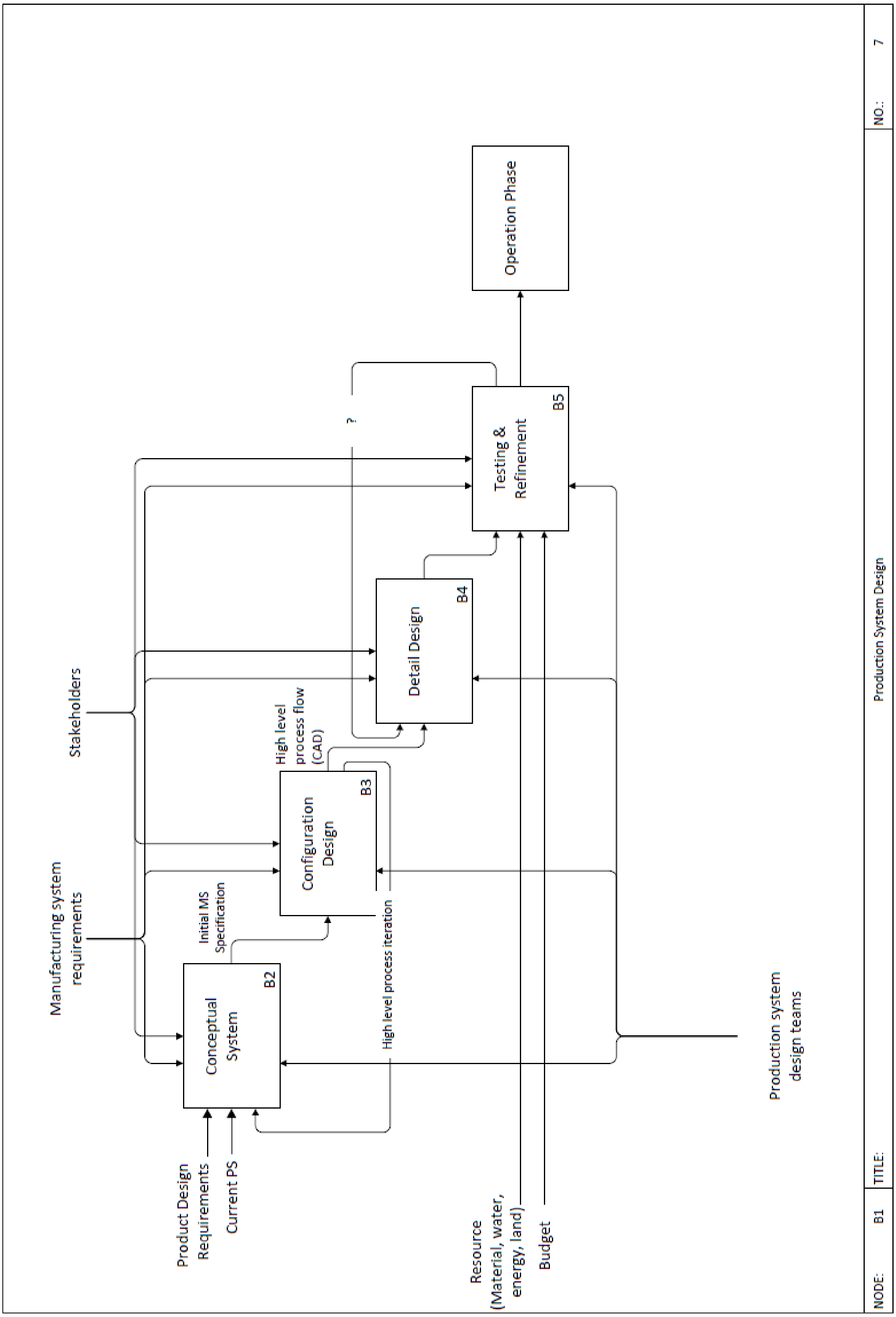

Product Requirements
Governments (Legislation Control)
COMPLETED Product Control Document (1. 2D & 3D CAD 2.BOM 3.Assembly Scheme)
Product Performance Testing
A18
Approved Test report
Regulation Approval
A19
Regulation Approval Document
Environmental Impact Assessment
A20
Environmental impact Document
Design Improvement
A21
COMPLETED Product Control Document (1. 2D & 3D CAD 2.BOM 3.Assembly Scheme 4.Prototype Sample)
Design Engineer Teams
Manufacturers
BOM & CAD (PDM SYSTEM)
NODE: A5
TITLE: Product Testing and Refinement
NO.: 5

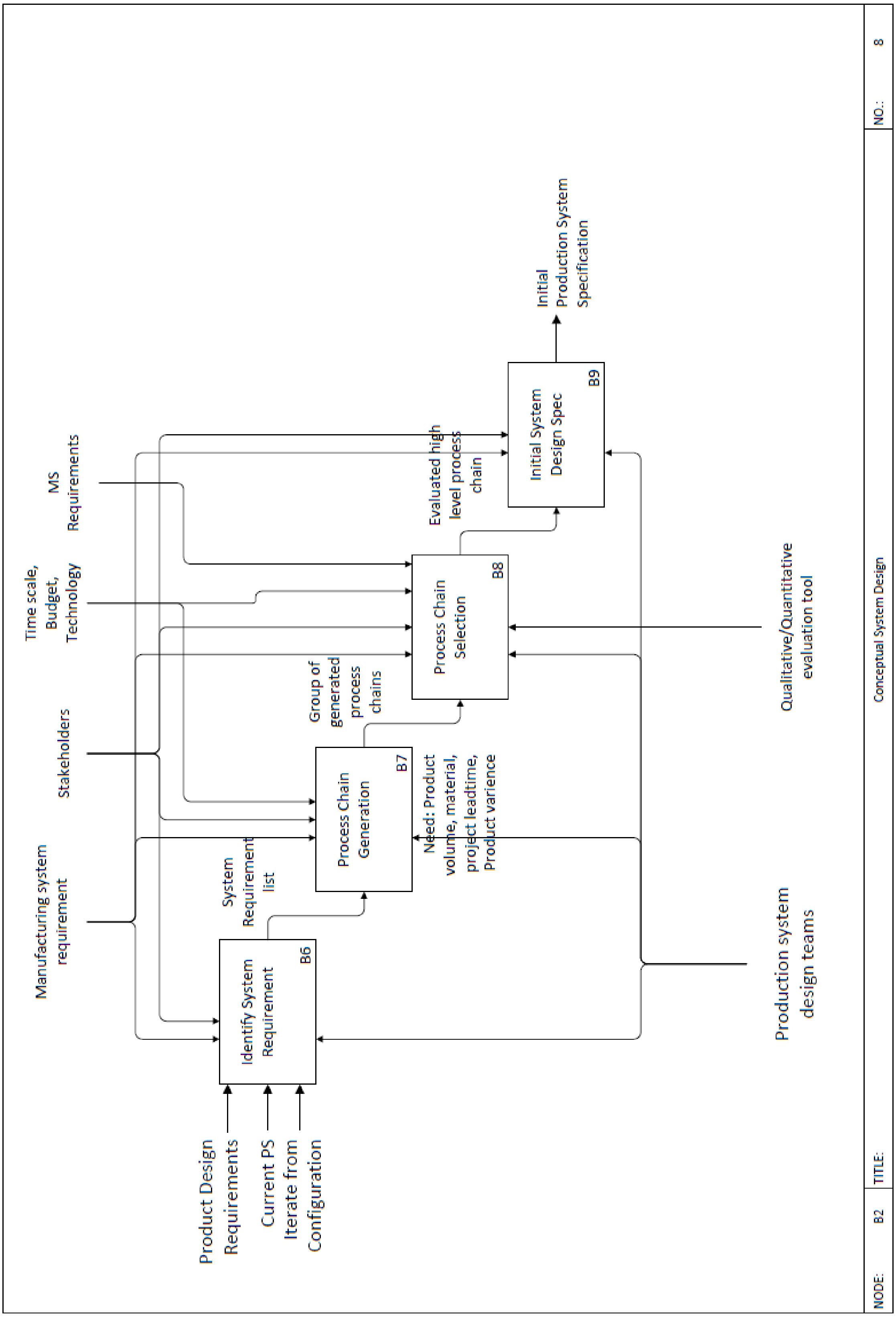
# APPENDIX II IDEF0 OF PRODUCTION SYSTEM DESIGN PROCESS

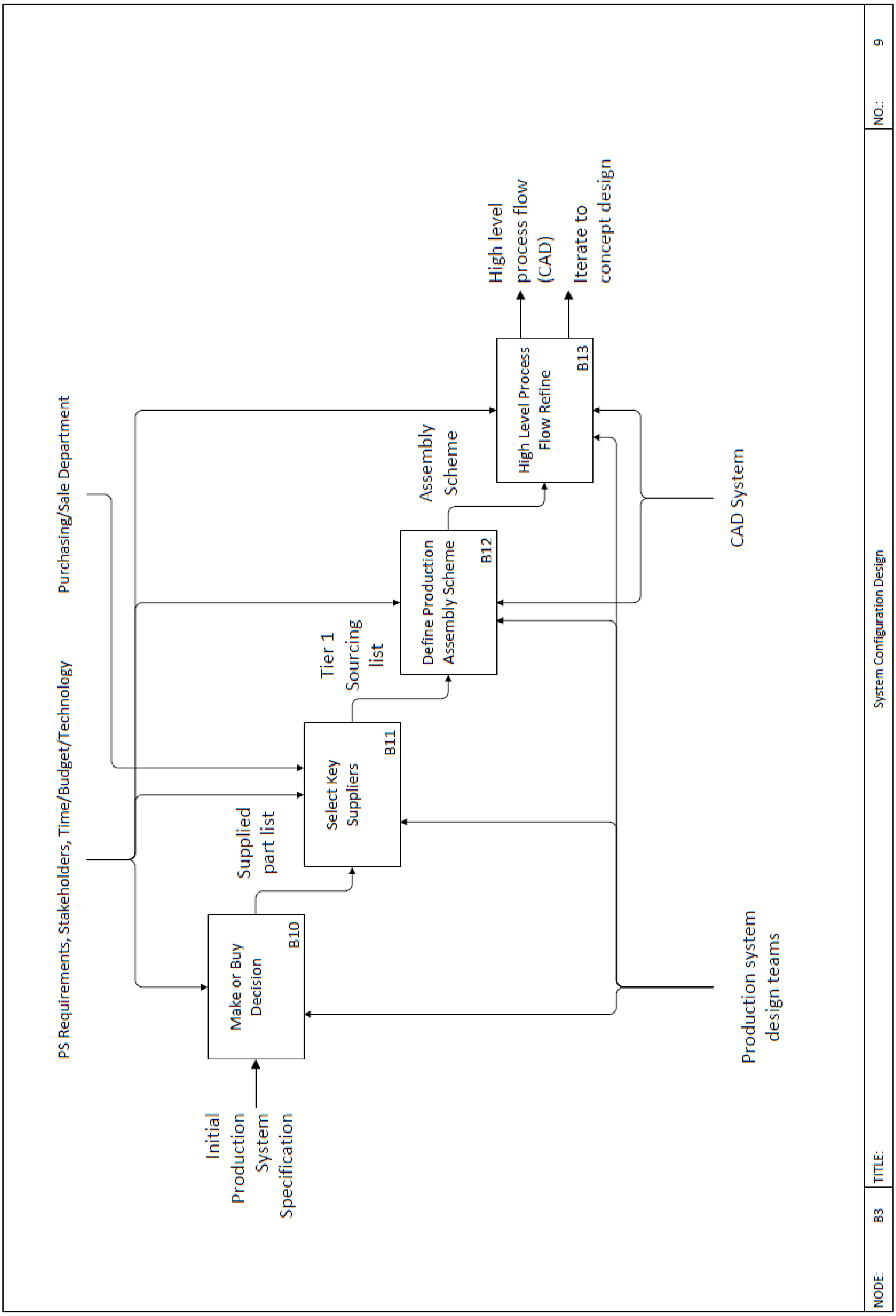
This appendix contains six pages involving three levels of the production system design process which are:

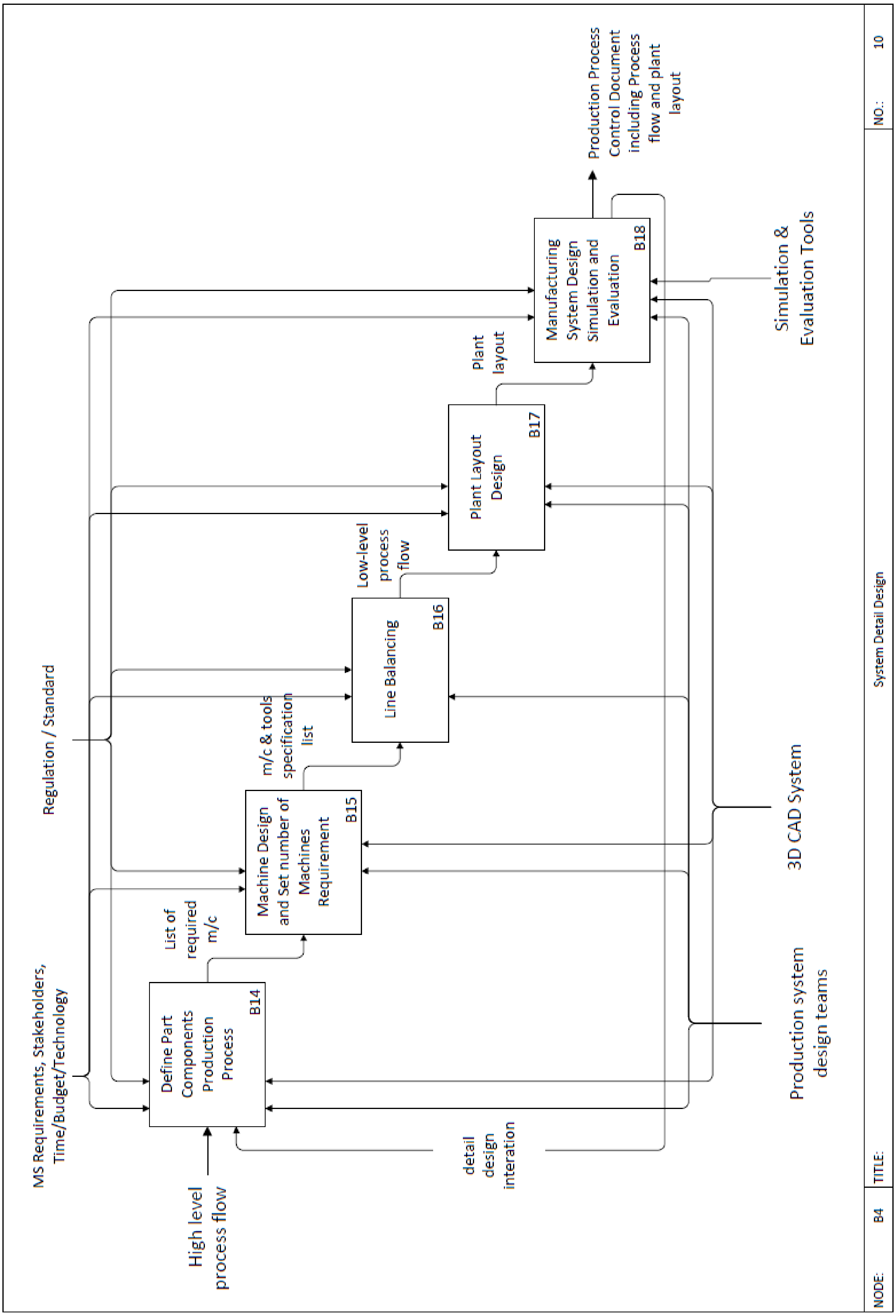
| | |
|---|---|
| Page A9 | Top level of the production system design process (Level 1) |
| Page A10 | Four design stages within the production system design process (Level 2) |
| Page A11 | Four design steps within the conceptual system stage (Level 3) |
| Page A12 | Four design steps within the system configuration design stage (Level 3) |
| Page A13 | Four design steps within the detail system design stage (Level 3) |
| Page A14 | Three design steps within system testing and refinement stage (Level 3) |

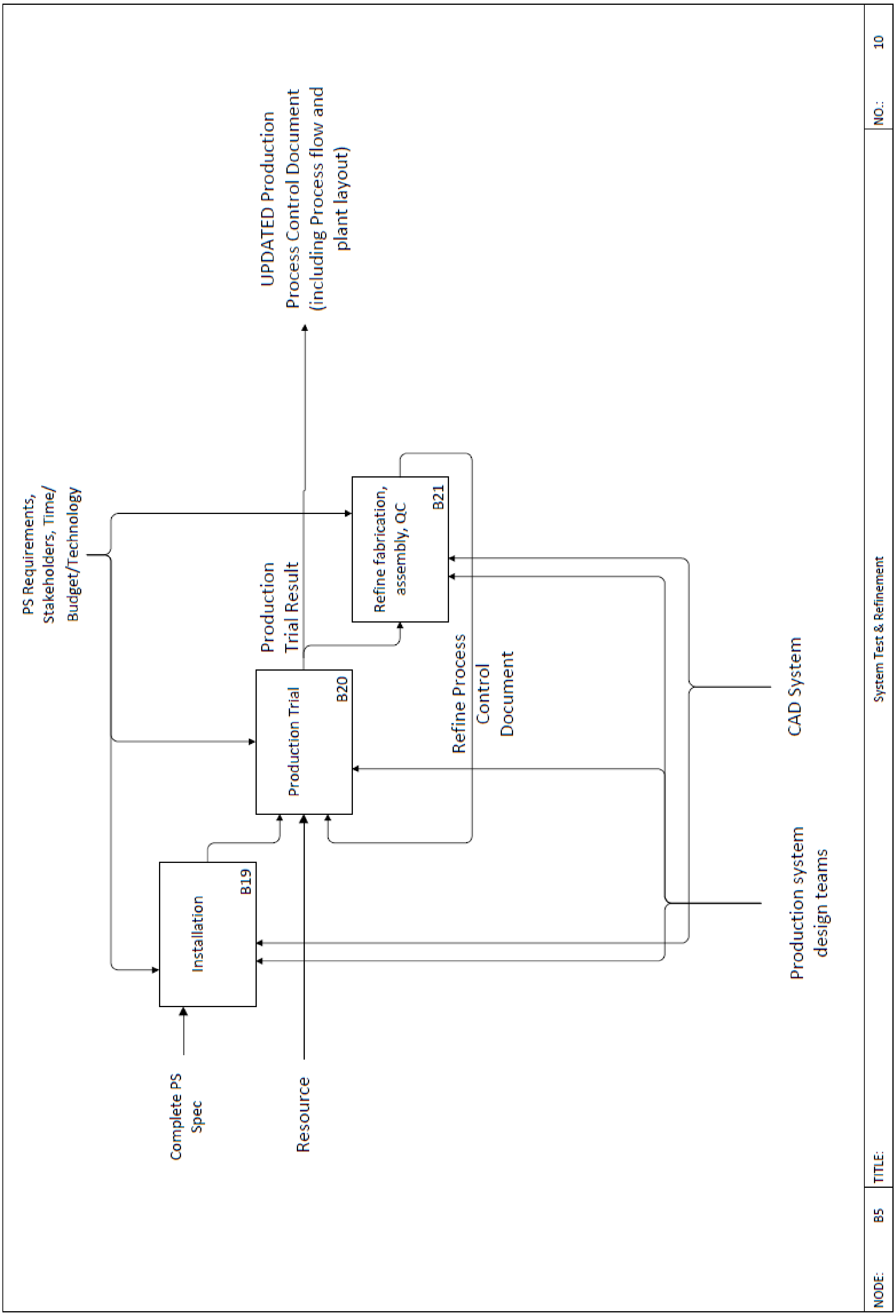

System Requirement
Stakeholders
Product Design Requirements
Current Production System
Production system design
B0
Production System
Production system design teams
NODE: B0
TITLE: Production System Design
NO.: 7


Manufacturing system requirements
Stakeholders
Product Design Requirements
Current PS
Conceptual System
B2
Initial MS Specification
Configuration Design
B3
High level process iteration
High level process flow (CAD)
Detail Design
B4
Testing & Refinement
B5
?
Operation Phase
Resource (Material, water, energy, land)
Budget
Production system design teams
NODE:
B1
TITLE:
Production System Design
NO.:
7


Manufacturing system requirement
Stakeholders
Time scale, Budget, Technology
MS Requirements
Product Design Requirements
Current PS
Iterate from Configuration
Identify System Requirement
B6
System Requirement list
Process Chain Generation
B7
Need: Product volume, material, project leadtime, Product varience
Group of generated process chains
Process Chain Selection
B8
Evaluated high level process chain
Initial System Design Spec
B9
Initial Production System Specification
Qualitative/Quantitative evaluation tool
Production system design teams
NODE:
B2
TITLE:
Conceptual System Design
NO.:
8


PS Requirements, Stakeholders, Time/Budget/Technology
Purchasing/Sale Department
Initial Production System Specification
Make or Buy Decision
B10
Supplied part list
Select Key Suppliers
B11
Tier 1 Sourcing list
Define Production Assembly Scheme
B12
Assembly Scheme
High Level Process Flow Refine
B13
High level process flow (CAD)
Iterate to concept design
CAD System
Production system design teams
NODE:
B3
TITLE:
System Configuration Design
NO.:
9


MS Requirements, Stakeholders, Time/Budget/Technology
Regulation / Standard
High level process flow
Define Part Components Production Process
B14
List of required m/c
Machine Design and Set number of Machines Requirement
B15
m/c & tools specification list
Line Balancing
B16
Low-level process flow
Plant Layout Design
B17
Plant layout
Manufacturing System Design Simulation and Evaluation
B18
Production Process Control Document including Process flow and plant layout
detail design interation
Production system design teams
3D CAD System
Simulation & Evaluation Tools
NODE:
B4
TITLE:
System Detail Design
NO.:
10


PS Requirements, Stakeholders, Time/ Budget/Technology
UPDATED Production Process Control Document (including Process flow and plant layout)
Complete PS Spec
Resource
Installation
B19
Production Trial
B20
Production Trial Result
Refine fabrication, assembly, QC
B21
Refine Process Control Document
Production system design teams
CAD System
NODE:
B5
TITLE:
System Test & Refinement
NO.:
10

# APPENDIX III PACKAGING CASE STUDY

This appendix illustrates the additional data, and result screens from the application of the simple design framework approach demonstrated in section 11.3 of this thesis. The contents of the appendix are as follows:

A3.1 The completed P&PS Co-design framework worksheets

A3.2 The completed calculation of resource consumption assessment

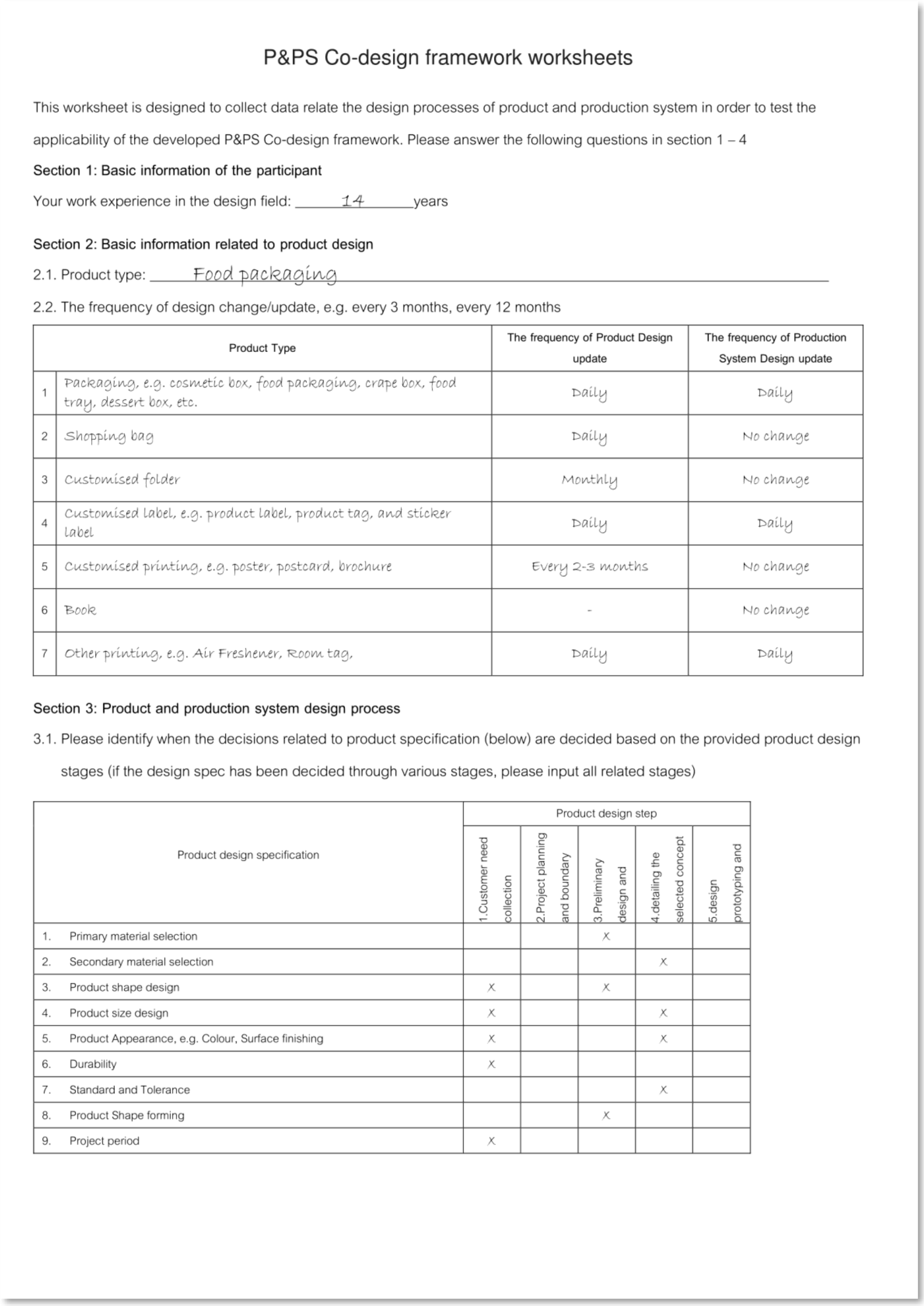
A3.3 Checklist for selecting resource efficient design strategy for product design

A3.4 Checklist for selecting resource efficient design strategy for production system design

A3.5 P&PS Design interrelation assessment

A3.6 Result of P&PS design process interrelation assessment from PPC software

## A3.1 The completed P&PS Co-design framework worksheets



### P&PS Co-design framework worksheets

This worksheet is designed to collect data relate the design processes of product and production system in order to test the applicability of the developed P&PS Co-design framework. Please answer the following questions in section 1 – 4

**Section 1: Basic information of the participant**

Your work experience in the design field: 14 years

**Section 2: Basic information related to product design**

2.1. Product type: Food packaging

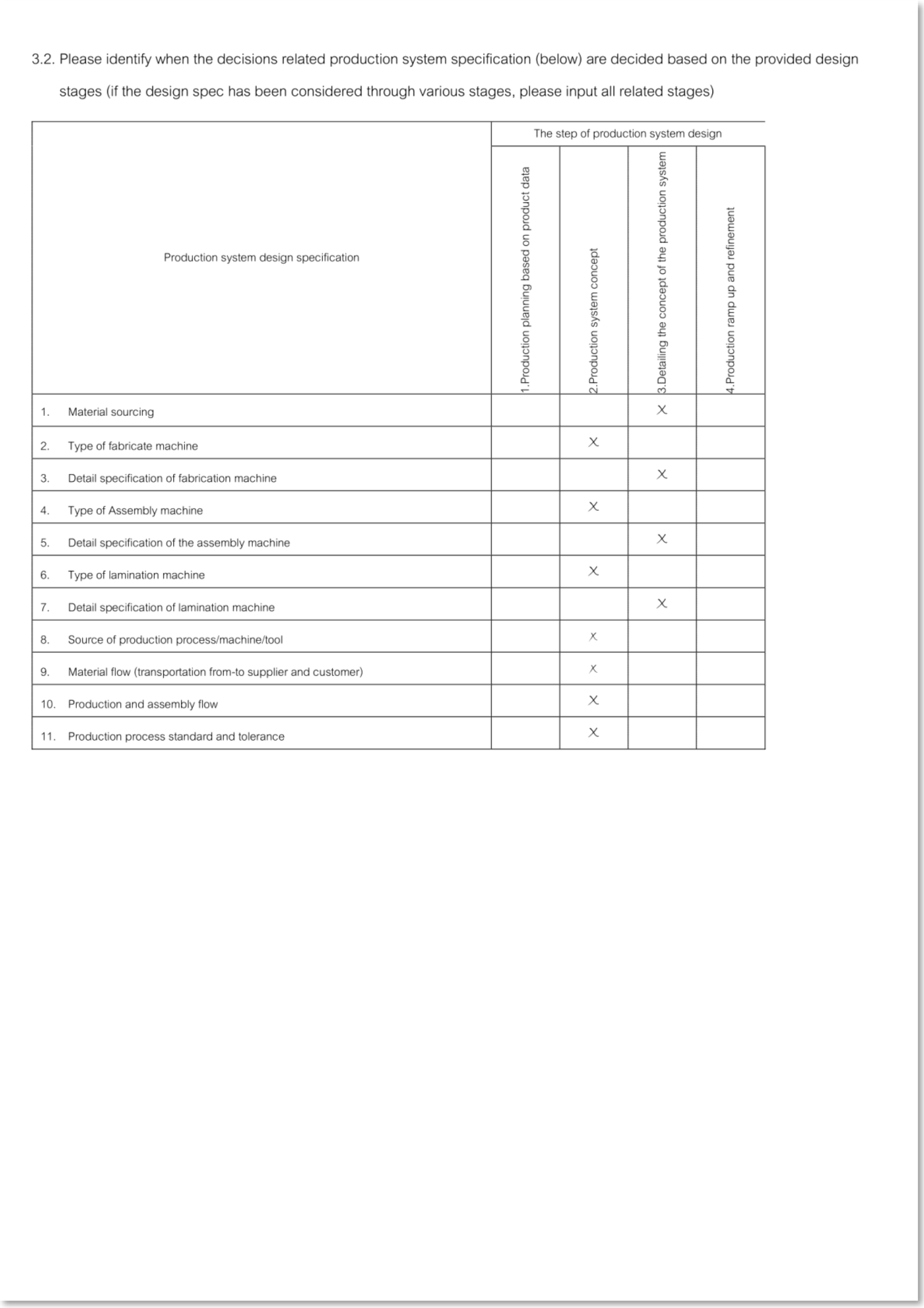
2.2. The frequency of design change/update, e.g. every 3 months, every 12 months

| Product Type | | The frequency of Product Design update | The frequency of Production System Design update |
|---|---|---|---|
| 1 | Packaging, e.g. cosmetic box, food packaging, crape box, food tray, dessert box, etc. | Daily | Daily |
| 2 | Shopping bag | Daily | No change |
| 3 | Customised folder | Monthly | No change |
| 4 | Customised label, e.g. product label, product tag, and sticker label | Daily | Daily |
| 5 | Customised printing, e.g. poster, postcard, brochure | Every 2-3 months | No change |
| 6 | Book | - | No change |
| 7 | Other printing, e.g. Air Freshener, Room tag, | Daily | Daily |

**Section 3: Product and production system design process**

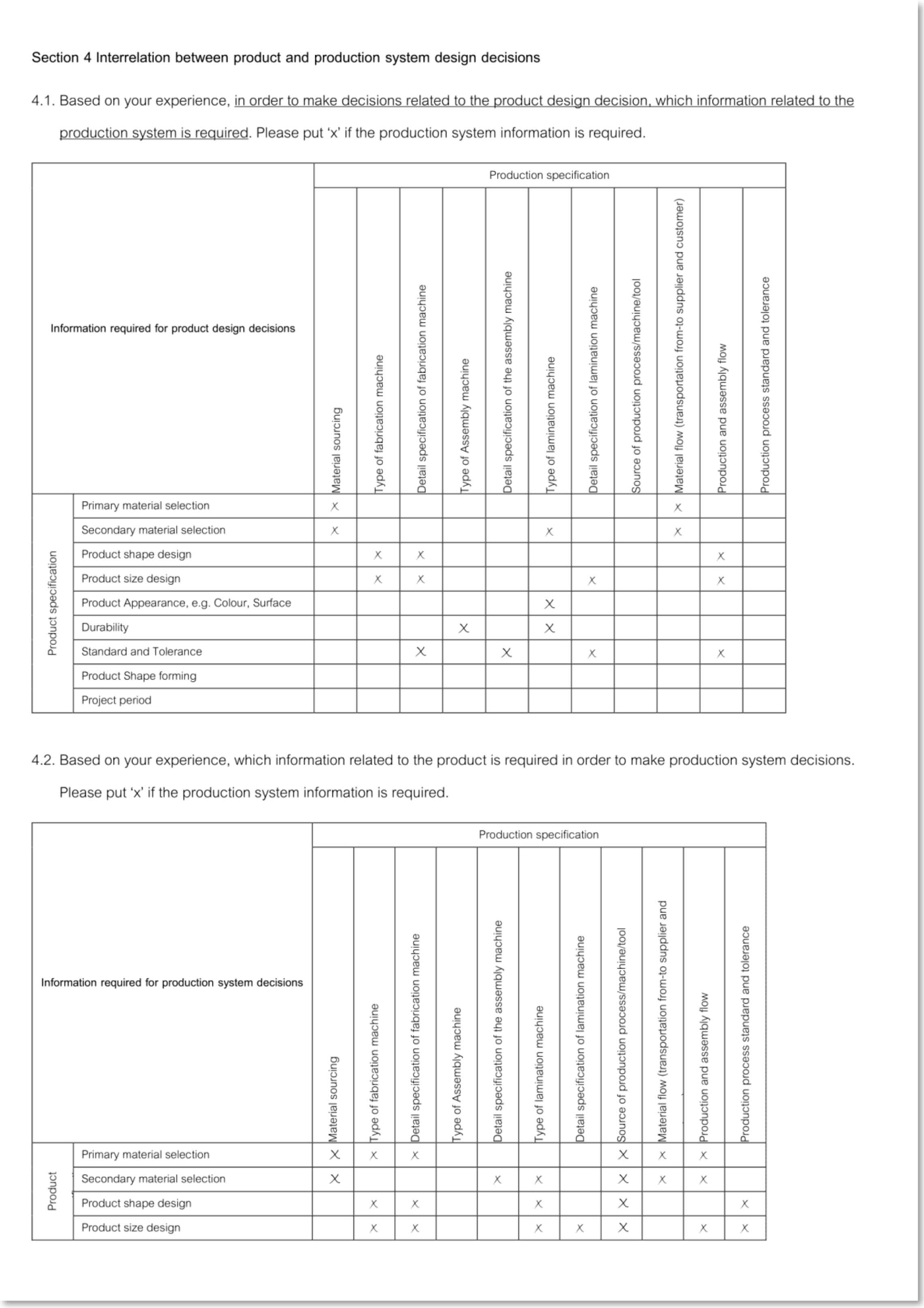
3.1. Please identify when the decisions related to product specification (below) are decided based on the provided product design stages (if the design spec has been decided through various stages, please input all related stages)

| Product design specification | Product design step | | | | |
|---|---|---|---|---|---|
| | 1.Customer need collection | 2.Project planning and boundary | 3.Preliminary design and | 4.detailing the selected concept | 5.design prototyping and |
| 1. Primary material selection | | | X | | |
| 2. Secondary material selection | | | | X | |
| 3. Product shape design | X | | X | | |
| 4. Product size design | X | | | X | |
| 5. Product Appearance, e.g. Colour, Surface finishing | X | | | X | |
| 6. Durability | X | | | | |
| 7. Standard and Tolerance | | | | X | |
| 8. Product Shape forming | | | X | | |
| 9. Project period | X | | | | |



3.2. Please identify when the decisions related production system specification (below) are decided based on the provided design stages (if the design spec has been considered through various stages, please input all related stages)

| Production system design specification | The step of production system design | | | |
|---|---|---|---|---|
| | 1.Production planning based on product data | 2.Production system concept | 3.Detailing the concept of the production system | 4.Production ramp up and refinement |
| 1. Material sourcing | | | X | |
| 2. Type of fabricate machine | | X | | |
| 3. Detail specification of fabrication machine | | | X | |
| 4. Type of Assembly machine | | X | | |
| 5. Detail specification of the assembly machine | | | X | |
| 6. Type of lamination machine | | X | | |
| 7. Detail specification of lamination machine | | | X | |
| 8. Source of production process/machine/tool | | X | | |
| 9. Material flow (transportation from-to supplier and customer) | | X | | |
| 10. Production and assembly flow | | X | | |
| 11. Production process standard and tolerance | | X | | |



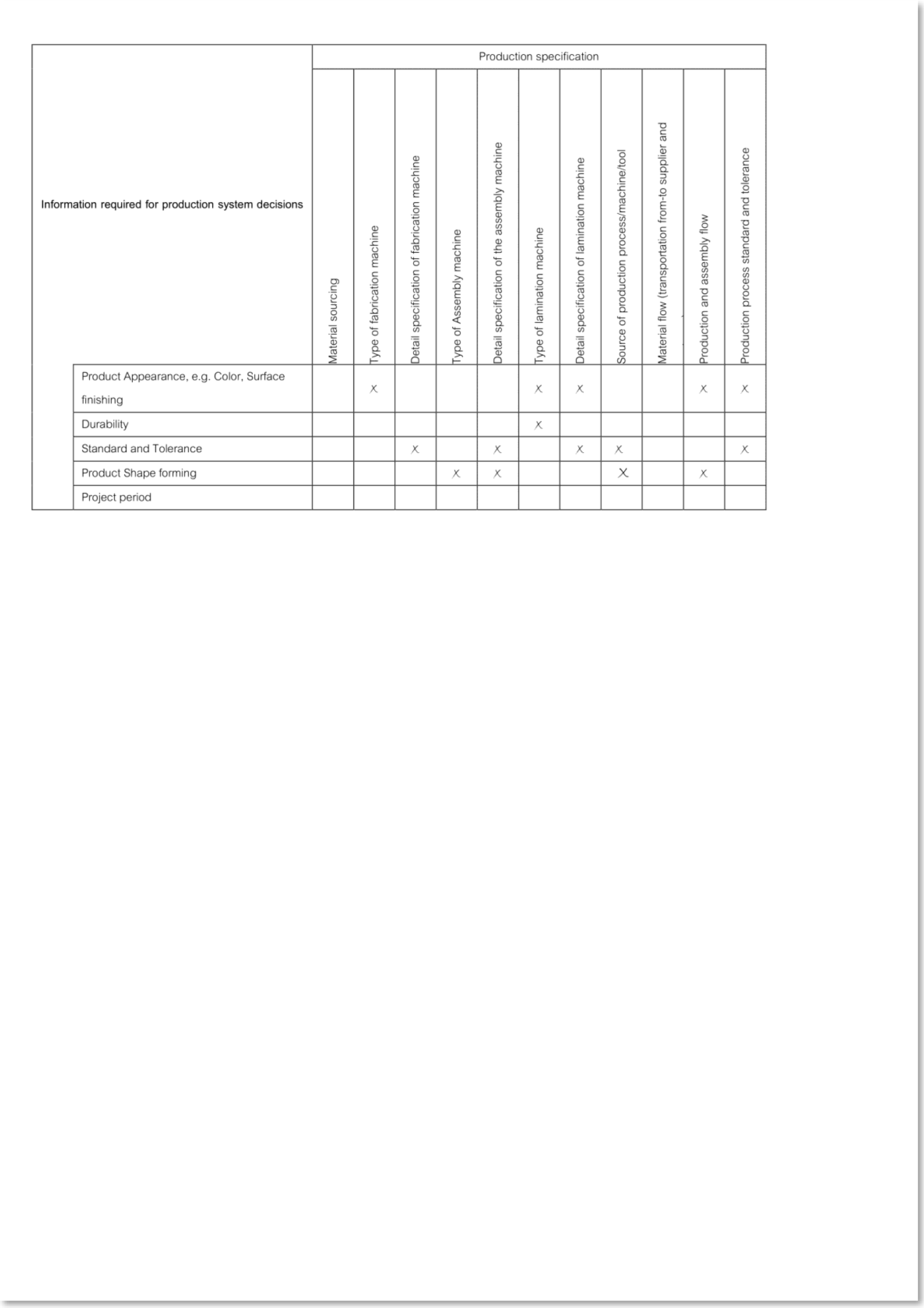
**Section 4 Interrelation between product and production system design decisions**

4.1. Based on your experience, in order to make decisions related to the product design decision, which information related to the production system is required. Please put ‘x’ if the production system information is required.

| **Information required for product design decisions** | | Production specification | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Material sourcing | Type of fabrication machine | Detail specification of fabrication machine | Type of Assembly machine | Detail specification of the assembly machine | Type of lamination machine | Detail specification of lamination machine | Source of production process/machine/tool | Material flow (transportation from-to supplier and customer) | Production and assembly flow | Production process standard and tolerance |
| Product specification | Primary material selection | x | | | | | | | | x | | |
| | Secondary material selection | x | | | | | x | | | x | | |
| | Product shape design | | x | x | | | | | | | x | |
| | Product size design | | x | x | | | | x | | | x | |
| | Product Appearance, e.g. Colour, Surface | | | | | | x | | | | | |
| | Durability | | | | x | | x | | | | | |
| | Standard and Tolerance | | | x | | x | | x | | | x | |
| | Product Shape forming | | | | | | | | | | | |
| | Project period | | | | | | | | | | | |

4.2. Based on your experience, which information related to the product is required in order to make production system decisions. Please put ‘x’ if the production system information is required.

| **Information required for production system decisions** | | Production specification | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Material sourcing | Type of fabrication machine | Detail specification of fabrication machine | Type of Assembly machine | Detail specification of the assembly machine | Type of lamination machine | Detail specification of lamination machine | Source of production process/machine/tool | Material flow (transportation from-to supplier and | Production and assembly flow | Production process standard and tolerance |
| Product | Primary material selection | x | x | x | | | | | x | x | x | |
| | Secondary material selection | x | | | | x | x | | x | x | x | |
| | Product shape design | | x | x | | | x | | x | | | x |
| | Product size design | | x | x | | | x | x | x | | x | x |

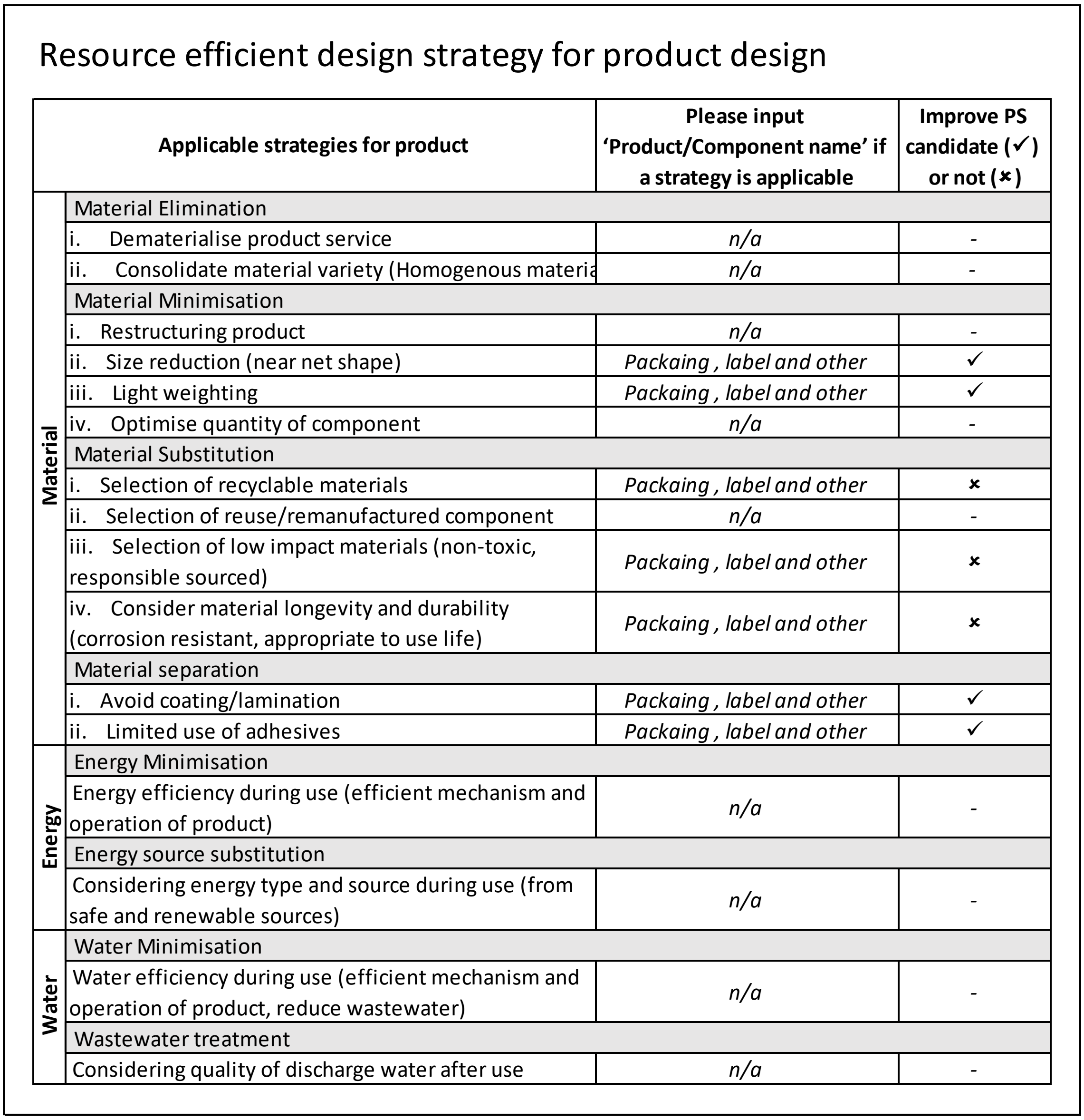


| Information required for production system decisions | Production specification | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Material sourcing | Type of fabrication machine | Detail specification of fabrication machine | Type of Assembly machine | Detail specification of the assembly machine | Type of lamination machine | Detail specification of lamination machine | Source of production process/machine/tool | Material flow (transportation from-to supplier and | Production and assembly flow | Production process standard and tolerance |
| Product Appearance, e.g. Color, Surface finishing | | X | | | | X | X | | | X | X |
| Durability | | | | | | X | | | | | |
| Standard and Tolerance | | | X | | X | | X | X | | | X |
| Product Shape forming | | | | X | X | | | X | | X | |
| Project period | | | | | | | | | | | |

## A3.2 The complete calculation of resource consumption assessment

| No. | Process | Material (Ton/annual) | | | | | Energy (kW/annual) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Type | Input | Output | Reject rate | Waste | Theoretical Energy | Auxiliary Energy | Direct Energy | Indirect Energy | Efficiency ratio |
| 1 | Block Screen | Steel plate | 0.51 | | 100.00% | 0.51 | - | 20.00 | - | 990.56 | - |
| 2 | Printer A | Paper | 326.11 | 309.80 | 5.00% | 16.31 | 7,000.00 | 4,200.00 | 11,200.00 | 990.56 | 62.50% |
| 3 | Printer B | Paper | 1,095.73 | 1,038.33 | 5.24% | 57.40 | 14,000.00 | 7,400.00 | 21,400.00 | 990.56 | 65.42% |
| 4 | Printer C | Paper | 907.89 | 862.49 | 5.00% | 45.40 | 9,000.00 | 5,400.00 | 14,400.00 | 990.56 | 62.50% |
| 5 | Printer D | Kraft paper | 2,008.83 | 1,988.74 | 1.00% | 20.09 | 10,000.00 | 3,600.00 | 13,600.00 | 990.56 | 73.53% |
| 6 | Drying | - | - | - | - | - | - | - | - | - | - |
| 7 | Coat A | Paper | 309.80 | 294.31 | 5.00% | 15.49 | 500.00 | 100.00 | 600.00 | 990.56 | 83.33% |
| | | Plastic A | 140.88 | 133.84 | | 7.04 | - | - | - | - | - |
| 8 | Coat B | Paper | 980.94 | 785.65 | 19.91% | 195.29 | 1,000.00 | 200.00 | 1,200.00 | 990.56 | 83.33% |
| | | Plastic B | 383.50 | 307.15 | | 76.35 | - | - | - | - | - |
| 9 | Coat C | Paper | 860.93 | 818.91 | 4.88% | 42.02 | 420.00 | 84.00 | 504.00 | 990.56 | 83.33% |
| | | Plastic C | 345.00 | 328.16 | | 16.84 | - | - | - | - | - |
| 10 | Coat D | Kraft paper | 1,914.91 | 1,758.24 | 8.18% | 156.67 | 9,000.00 | 1,800.00 | 10,800.00 | 990.56 | 83.33% |
| | | Aluminium foil | 703.09 | 645.57 | | 57.52 | - | - | - | - | - |
| 11 | Cutting A | Paper | 294.31 | 223.62 | **24.02%** | 70.69 | 5,550.00 | 2,220.00 | 7,770.00 | 990.56 | 71.43% |
| | | Plastic A | 133.84 | 101.69 | **24.02%** | 32.15 | | | | | |
| 12 | Cutting BC | Paper | 1,604.56 | 1,231.18 | **23.27%** | 373.38 | 5,550.00 | 2,220.00 | 7,770.00 | 990.56 | 71.43% |
| | | Plastic B | 307.15 | 235.68 | **23.27%** | 71.47 | | | | | |
| | | Plastic C | 328.16 | 251.80 | **23.27%** | 76.36 | | | | | |
| 13 | Cutting D | Kraft paper | 1,406.59 | 1,054.95 | **25.00%** | 351.65 | 425.00 | 170.00 | 595.00 | 990.56 | 71.43% |
| | | Aluminium foil | 645.57 | 484.18 | **25.00%** | 161.39 | | | | | |
| 14 | Cutting E | Kraft paper | 351.65 | 239.12 | **32.00%** | 112.53 | 425.00 | 170.00 | 595.00 | 990.56 | 71.43% |
| 15 | Folding | Paper | 223.62 | 221.38 | 1.00% | 2.24 | 1,140.00 | 342.00 | 1,482.00 | 990.56 | 76.92% |
| | | Plastic A | 101.69 | 100.67 | 1.00% | 1.02 | | | | | |
| 16 | Forming | Kraft paper | 1,054.95 | 1,044.40 | 1.00% | 10.55 | 960.00 | 288.00 | 1,248.00 | 990.56 | 76.92% |
| | | Aluminium foil | 484.18 | 479.33 | 1.00% | 4.84 | | | | | |
| | | | 16,914.37 | 14,939.17 | 11.68% | 1,975.20 | 64,970.00 | 28,214.00 | 93,164.00 | 15,849.00 | |

## A3.3 Checklist for selecting resource efficient design strategy for product design



### Resource efficient design strategy for product design

| Applicable strategies for product | | Please input 'Product/Component name' if a strategy is applicable | Improve PS candidate (✓) or not (×) |
|---|---|---|---|
| Material | Material Elimination | | |
| | i. Dematerialise product service | *n/a* | - |
| | ii. Consolidate material variety (Homogenous materi | *n/a* | - |
| | Material Minimisation | | |
| | i. Restructuring product | *n/a* | - |
| | ii. Size reduction (near net shape) | *Packaing , label and other* | ✓ |
| | iii. Light weighting | *Packaing , label and other* | ✓ |
| | iv. Optimise quantity of component | *n/a* | - |
| | Material Substitution | | |
| | i. Selection of recyclable materials | *Packaing , label and other* | × |
| | ii. Selection of reuse/remanufactured component | *n/a* | - |
| | iii. Selection of low impact materials (non-toxic, responsible sourced) | *Packaing , label and other* | × |
| | iv. Consider material longevity and durability (corrosion resistant, appropriate to use life) | *Packaing , label and other* | × |
| | Material separation | | |
| | i. Avoid coating/lamination | *Packaing , label and other* | ✓ |
| | ii. Limited use of adhesives | *Packaing , label and other* | ✓ |
| Energy | Energy Minimisation | | |
| | Energy efficiency during use (efficient mechanism and operation of product) | *n/a* | - |
| | Energy source substitution | | |
| | Considering energy type and source during use (from safe and renewable sources) | *n/a* | - |
| Water | Water Minimisation | | |
| | Water efficiency during use (efficient mechanism and operation of product, reduce wastewater) | *n/a* | - |
| | Wastewater treatment | | |
| | Considering quality of discharge water after use | *n/a* | - |

## A3.4 Checklist for selecting resource efficient design strategy for product design

### Resource efficient strategy for production system design

| Applicable SD approaches for production system | Please input 'Product/Component name' if a strategy is applicable | Improve PS candidate (✓) or not (×) |
|---|---|---|
| **Material** | | |
| i. Near net shape | *Packaing , label and other* | ✓ |
| ii. Waste in process minimisation | *Packaing , label and other* | ✓ |
| iii. Selection of process which produce low/zero waste | *Packaing , label and other* | ✓ |
| iv. Efficient packaging (minimised packaging materials and volume of packages) | *Packaing , label and other* | × |
| v. Adoption of remanufacturing process | *Packaing , label and other* | × |
| vi. Adoption of recycling process | *Packaing , label and other* | × |
| vii. Adoption of take back and collection methods | | |
| **Energy** | | |
| i. Minimise operation (Eliminate unnecessary operation) | *Packaing , label and other* | ✓ |
| ii. Selection of process which consume less energy (energy efficiency in production process) | *Packaing , label and other* | ✓ |
| iii. Selection of energy type and source used in production (safe and renewable source) | *Packaing , label and other* | × |
| iv. Transportation method | *Packaing , label and other* | × |
| v. Geographical location of manufacturing, operations and suppliers (Shortening Distance of transportation) | *Packaing , label and other* | × |
| **Water** | | |
| i. Waste water minimisation | *n/a* | - |
| ii. Contaminated/Grey water minimisation | *n/a* | - |
| iii. Water recycling | *n/a* | - |

## A3.5 P&PS Design interrelation assessment

### Interrelation assessment sheet - Product design

**Product: Packaging, Label and other printing**

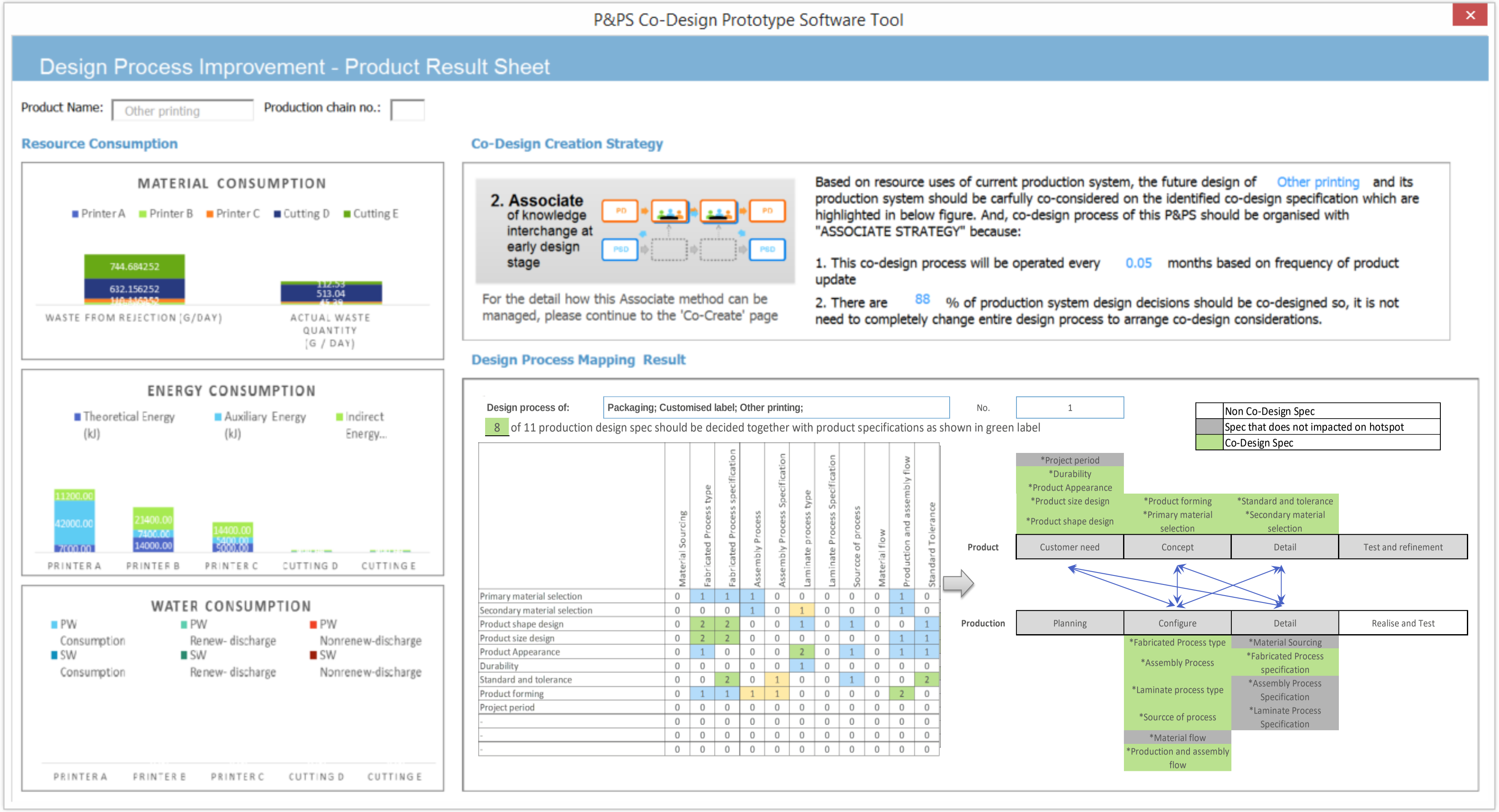
| | | Production specification | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Material sourcing | Type of frabricate machine | Datail specification of fabricate machine | Type of Assembly machine | Detail specification of assembly machine | Type of lamination machine | Detail specification of lamination machine | Source of production process/machine/tool | Material flow (transportation from-to suppli | Production and assembly flow | Production process standard and tolerance |
| Product specification | Primary material selection | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Secondary material selection | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 |
| | Product shape design | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Product size design | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Product Appearance e.g. | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 |
| | Durability | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Standard and Tolerance | 0 | 0 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 1 |
| | Product Shape forming | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 1 | 0 |
| | Project period | | | | | | | | | | | |

### Interrelation assessment sheet - Production system design

**Product: Packaging, Label and other printing**

| | | Production specification | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Material sourcing | Type of frabricate machine | Datail specification of fabricate machine | Type of Assembly machine | Detail specification of assembly machine | Type of lamination machine | Detail specification of lamination machine | Source of production process/machine/tool | Material flow (transportation from-to suppli | Production and assembly flow | Production process standard and tolerance |
| Product specification | Primary material selection | | 1 | 1 | 1 | | 0 | | 0 | | 1 | 0 |
| | Secondary material selection | | 0 | 0 | 1 | | 1 | | 1 | | 1 | 0 |
| | Product shape design | | 1 | 1 | 0 | | 0 | | 0 | | 0 | 1 |
| | Product size design | | 1 | 1 | 0 | | 1 | | 1 | | 1 | 1 |
| | Product Appearance e.g. Color, Surface | | 1 | 0 | 0 | | 1 | | 0 | | 1 | 1 |
| | Durability | | 0 | 0 | 0 | | 0 | | 0 | | 0 | 0 |
| | Standard and Tolerance | | 0 | 1 | 0 | | 0 | | 1 | | 0 | 1 |
| | Product Shape forming | | 1 | 1 | 0 | | 0 | | 0 | | 1 | 0 |
| | Project period | | 0 | 0 | 0 | | 0 | | 0 | | 0 | 0 |

# A3.6 Result of P&PS design process interrelation assessment from PPC software



Product Name: Other printing
Production chain no.:

**Resource Consumption**

**Co-Design Creation Strategy**

For the detail how this Associate method can be managed, please continue to the 'Co-Create' page

Based on resource uses of current production system, the future design of Other printing and its production system should be carfully co-considered on the identified co-design specification which are highlighted in below figure. And, co-design process of this P&PS should be organised with "ASSOCIATE STRATEGY" because:

1. This co-design process will be operated every 0.05 months based on frequency of product update

2. There are 88 % of production system design decisions should be co-designed so, it is not need to completely change entire design process to arrange co-design considerations.

**Design Process Mapping Result**

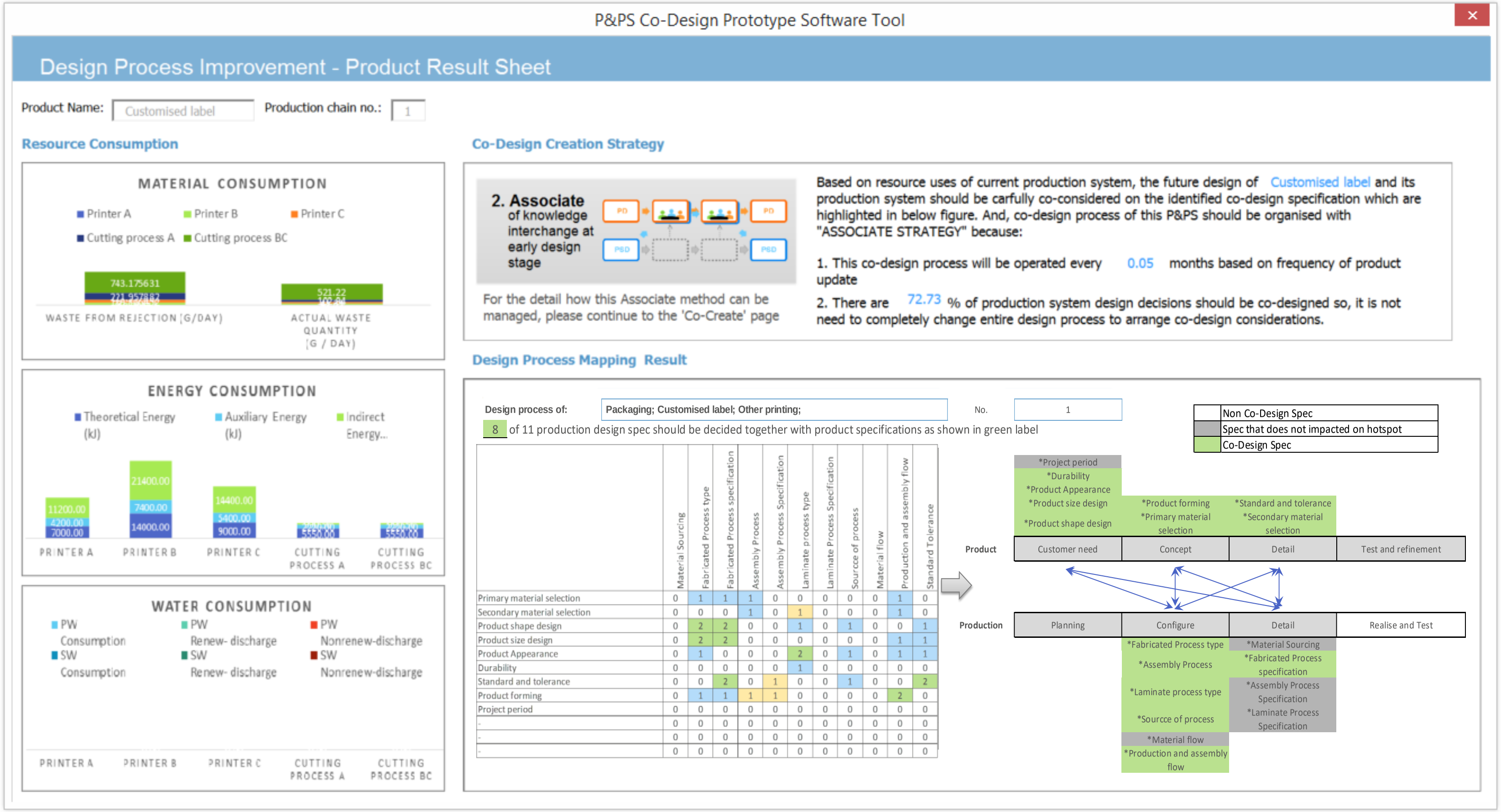
Design process of: Packaging; Customised label; Other printing;
No. 1

8 of 11 production design spec should be decided together with product specifications as shown in green label

| | Material Sourcing | Fabricated Process type | Fabricated Process specification | Assembly Process | Assembly Process Specification | Laminate process type | Laminate Process Specification | Sourcce of process | Material flow | Production and assembly flow | Standard Tolerance |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Primary material selection | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 0 |
| Secondary material selection | 0 | 0 | 0 | 1 | 0 | 1 | 0 | 0 | 0 | 1 | 0 |
| Product shape design | 0 | 2 | 2 | 0 | 0 | 1 | 0 | 1 | 0 | 0 | 1 |
| Product size design | 0 | 2 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 |
| Product Appearance | 0 | 1 | 0 | 0 | 0 | 2 | 0 | 1 | 0 | 1 | 1 |
| Durability | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 |
| Standard and tolerance | 0 | 0 | 2 | 0 | 1 | 0 | 0 | 1 | 0 | 0 | 2 |
| Product forming | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 2 | 0 |
| Project period | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| - | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| - | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| - | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

| | |
|---|---|
| ☐ | Non Co-Design Spec |
| ▨ | Spec that does not impacted on hotspot |
| 🟩 | Co-Design Spec |

## A3.6 Result of P&PS design process interrelation assessment from PPC software (continue)



# Design Process Improvement - Product Result Sheet

Product Name: Customised label Production chain no.: 1

**Resource Consumption**

**Co-Design Creation Strategy**

For the detail how this Associate method can be managed, please continue to the 'Co-Create' page

Based on resource uses of current production system, the future design of Customised label and its production system should be carfully co-considered on the identified co-design specification which are highlighted in below figure. And, co-design process of this P&PS should be organised with "ASSOCIATE STRATEGY" because:

1. This co-design process will be operated every 0.05 months based on frequency of product update

2. There are 72.73 % of production system design decisions should be co-designed so, it is not need to completely change entire design process to arrange co-design considerations.

**Design Process Mapping Result**

Design process of: Packaging; Customised label; Other printing; No. 1

8 of 11 production design spec should be decided together with product specifications as shown in green label

| | Material Sourcing | Fabricated Process type | Fabricated Process specification | Assembly Process | Assembly Process Specification | Laminate process type | Laminate Process Specification | Sourcce of process | Material flow | Production and assembly flow | Standard Tolerance |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Primary material selection | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 0 |
| Secondary material selection | 0 | 0 | 0 | 1 | 0 | 1 | 0 | 0 | 0 | 1 | 0 |
| Product shape design | 0 | 2 | 2 | 0 | 0 | 1 | 0 | 1 | 0 | 0 | 1 |
| Product size design | 0 | 2 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 |
| Product Appearance | 0 | 1 | 0 | 0 | 0 | 2 | 0 | 1 | 0 | 1 | 1 |
| Durability | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 |
| Standard and tolerance | 0 | 0 | 2 | 0 | 1 | 0 | 0 | 1 | 0 | 0 | 2 |
| Product forming | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 2 | 0 |
| Project period | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| - | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| - | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| - | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

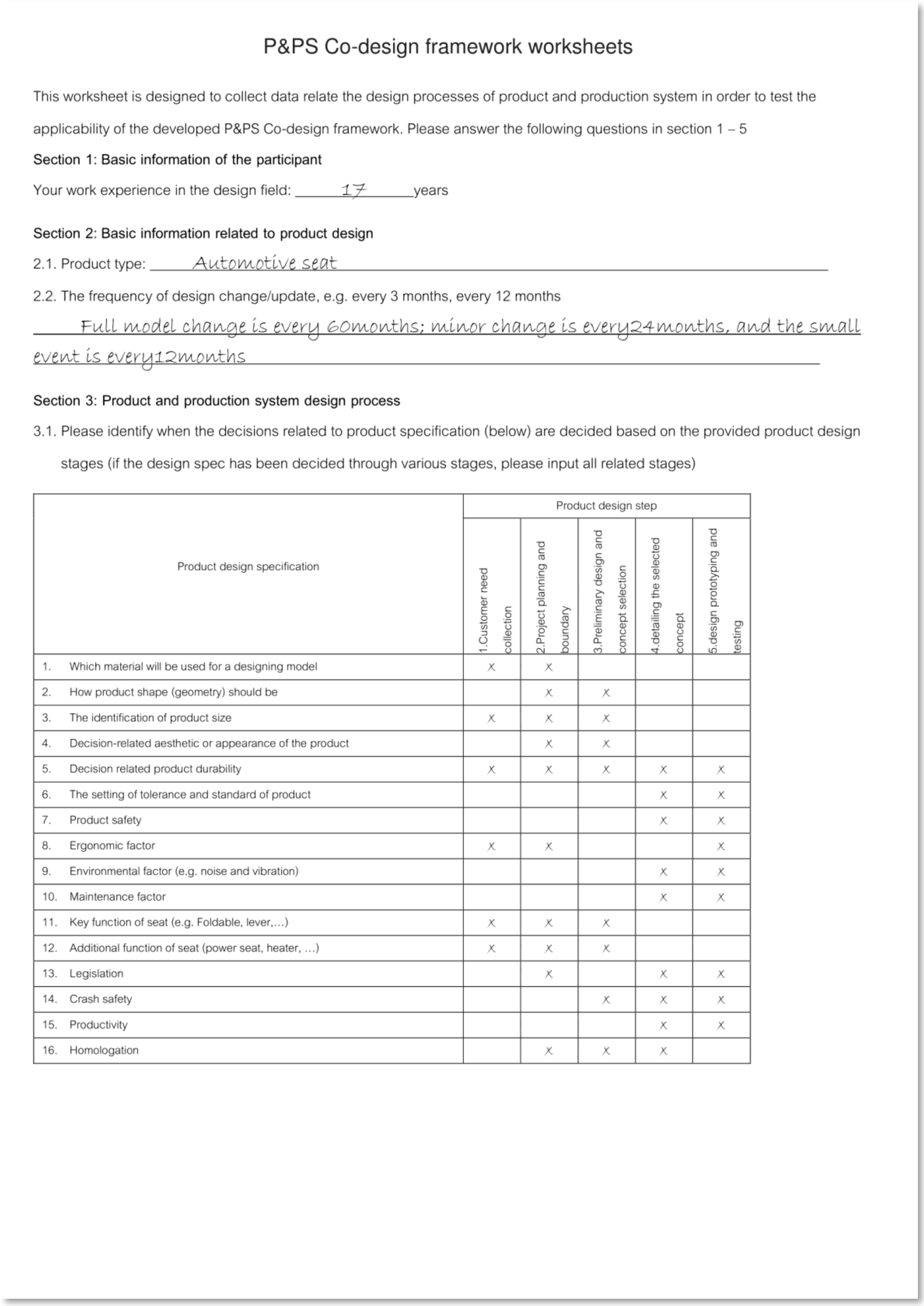
| | |
|---|---|
| ☐ | Non Co-Design Spec |
| ▨ | Spec that does not impacted on hotspot |
| 🟩 | Co-Design Spec |

# APPENDIX IV AUTOMOTIVE SEAT CASE STUDY

This appendix illustrates the additional data, and result screens from the application of the simple design framework approach demonstrated in section 11.4 of this thesis. The contents of the appendix are as follows:

| | |
|---|---|
| A4.1 | The completed P&PS Co-design framework worksheets |
| A4.2 | Data supporting resource consumption assessment |
| A4.3 | The complete calculation of resource consumption assessment |
| A4.4 | Checklist for selecting resource efficient design strategy for product design |
| A4.5 | Checklist for selecting resource efficient design strategy for production system design |
| A4.6 | P&PS Design interrelation assessment (seat frame) |
| A4.7 | P&PS Design interrelation assessment (seat pad foam) |
| A4.8 | P&PS Design interrelation assessment (seat trim cover) |
| A4.9 | The original P&PS Design processes supporting creation of a single process |

## A4.1 The completed P&PS Co-design framework worksheets



### P&PS Co-design framework worksheets

This worksheet is designed to collect data relate the design processes of product and production system in order to test the applicability of the developed P&PS Co-design framework. Please answer the following questions in section 1 – 5

**Section 1: Basic information of the participant**

Your work experience in the design field: 17 years

**Section 2: Basic information related to product design**

2.1. Product type: Automotive seat

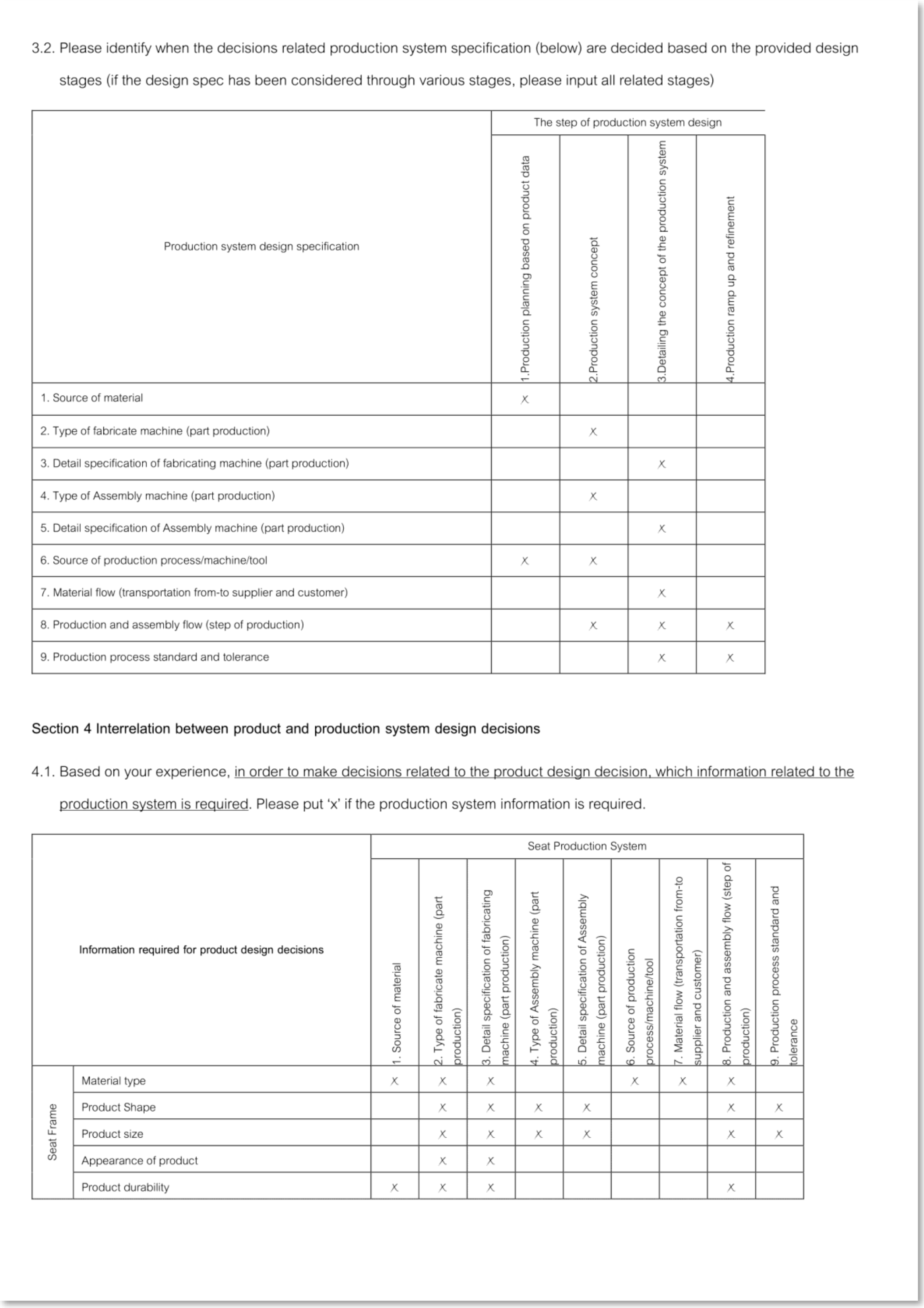
2.2. The frequency of design change/update, e.g. every 3 months, every 12 months

Full model change is every 60months; minor change is every24months, and the small event is every12months

**Section 3: Product and production system design process**

3.1. Please identify when the decisions related to product specification (below) are decided based on the provided product design stages (if the design spec has been decided through various stages, please input all related stages)

| Product design specification | | Product design step | | | | |
|---|---|---|---|---|---|---|
| | | 1.Customer need collection | 2.Project planning and boundary | 3.Preliminary design and concept selection | 4.detailing the selected concept | 5.design prototyping and testing |
| 1. | Which material will be used for a designing model | X | X | | | |
| 2. | How product shape (geometry) should be | | X | X | | |
| 3. | The identification of product size | X | X | X | | |
| 4. | Decision-related aesthetic or appearance of the product | | X | X | | |
| 5. | Decision related product durability | X | X | X | X | X |
| 6. | The setting of tolerance and standard of product | | | | X | X |
| 7. | Product safety | | | | X | X |
| 8. | Ergonomic factor | X | X | | | X |
| 9. | Environmental factor (e.g. noise and vibration) | | | | X | X |
| 10. | Maintenance factor | | | | X | X |
| 11. | Key function of seat (e.g. Foldable, lever,…) | X | X | X | | |
| 12. | Additional function of seat (power seat, heater, …) | X | X | X | | |
| 13. | Legislation | | X | | X | X |
| 14. | Crash safety | | | X | X | X |
| 15. | Productivity | | | | X | X |
| 16. | Homologation | | X | X | X | |



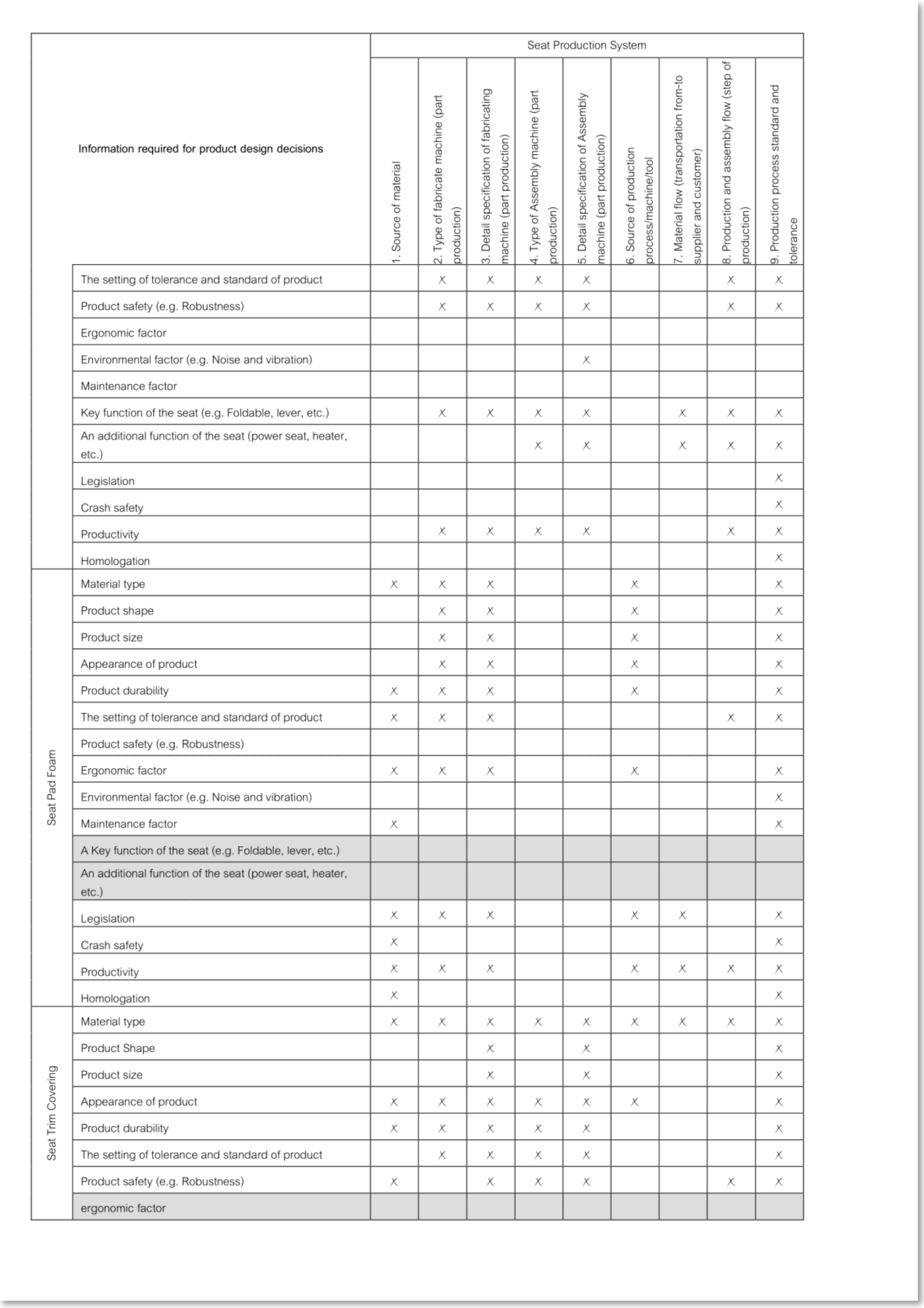
3.2. Please identify when the decisions related production system specification (below) are decided based on the provided design stages (if the design spec has been considered through various stages, please input all related stages)

| Production system design specification | The step of production system design | | | |
|---|---|---|---|---|
| | 1.Production planning based on product data | 2.Production system concept | 3.Detailing the concept of the production system | 4.Production ramp up and refinement |
| 1. Source of material | x | | | |
| 2. Type of fabricate machine (part production) | | x | | |
| 3. Detail specification of fabricating machine (part production) | | | x | |
| 4. Type of Assembly machine (part production) | | x | | |
| 5. Detail specification of Assembly machine (part production) | | | x | |
| 6. Source of production process/machine/tool | x | x | | |
| 7. Material flow (transportation from-to supplier and customer) | | | x | |
| 8. Production and assembly flow (step of production) | | x | x | x |
| 9. Production process standard and tolerance | | | x | x |

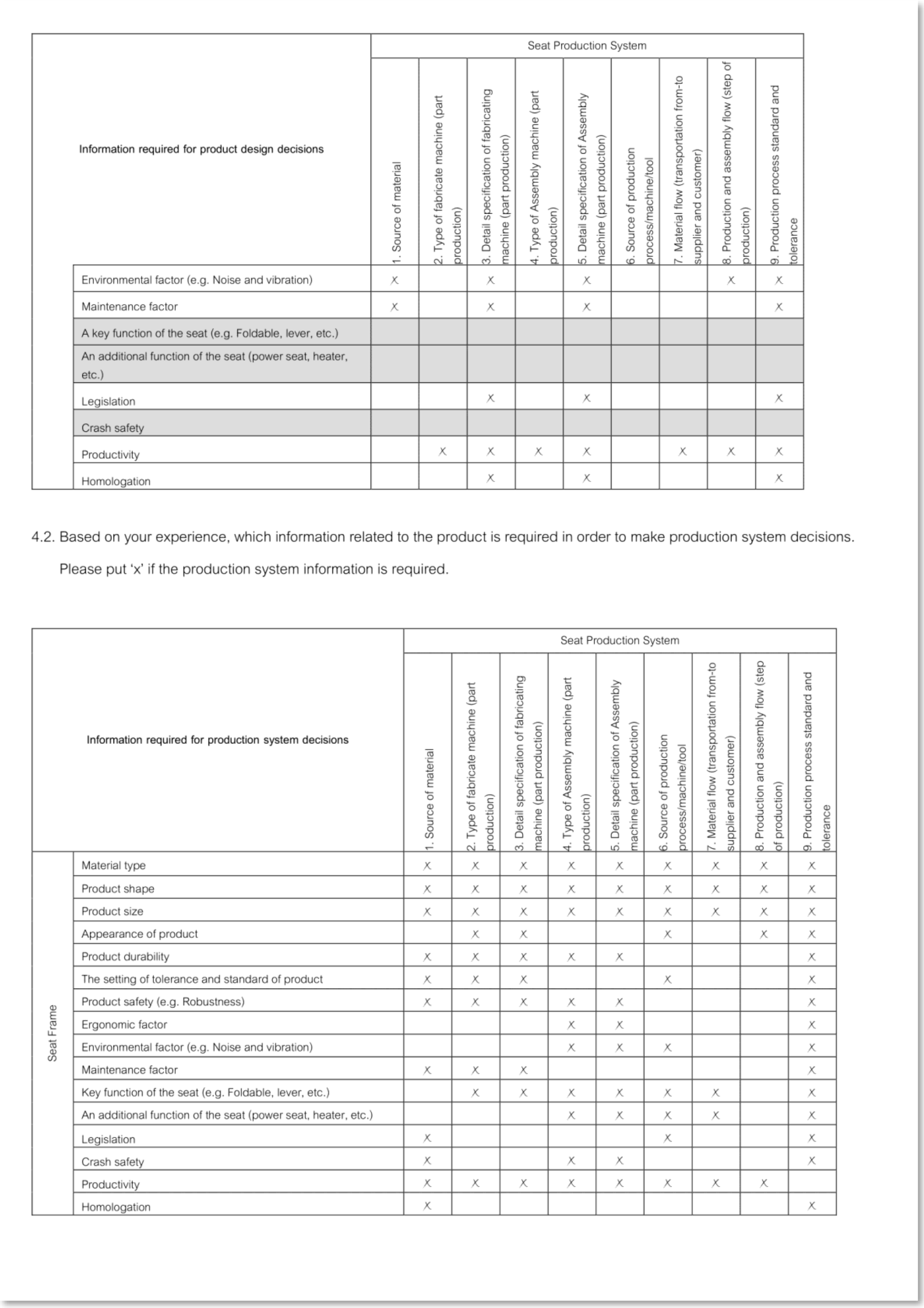
**Section 4 Interrelation between product and production system design decisions**

4.1. Based on your experience, <u>in order to make decisions related to the product design decision, which information related to the production system is required</u>. Please put 'x' if the production system information is required.

| Information required for product design decisions | | Seat Production System | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 1. Source of material | 2. Type of fabricate machine (part production) | 3. Detail specification of fabricating machine (part production) | 4. Type of Assembly machine (part production) | 5. Detail specification of Assembly machine (part production) | 6. Source of production process/machine/tool | 7. Material flow (transportation from-to supplier and customer) | 8. Production and assembly flow (step of production) | 9. Production process standard and tolerance |
| Seat Frame | Material type | x | x | x | | | x | x | x | |
| | Product Shape | | x | x | x | x | | | x | x |
| | Product size | | x | x | x | x | | | x | x |
| | Appearance of product | | x | x | | | | | | |
| | Product durability | x | x | x | | | | | x | |



| Information required for product design decisions | | Seat Production System | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 1. Source of material | 2. Type of fabricate machine (part production) | 3. Detail specification of fabricating machine (part production) | 4. Type of Assembly machine (part production) | 5. Detail specification of Assembly machine (part production) | 6. Source of production process/machine/tool | 7. Material flow (transportation from-to supplier and customer) | 8. Production and assembly flow (step of production) | 9. Production process standard and tolerance |
| | The setting of tolerance and standard of product | | X | X | X | X | | | X | X |
| | Product safety (e.g. Robustness) | | X | X | X | X | | | X | X |
| | Ergonomic factor | | | | | | | | | |
| | Environmental factor (e.g. Noise and vibration) | | | | | X | | | | |
| | Maintenance factor | | | | | | | | | |
| | Key function of the seat (e.g. Foldable, lever, etc.) | | X | X | X | X | | X | X | X |
| | An additional function of the seat (power seat, heater, etc.) | | | | X | X | | X | X | X |
| | Legislation | | | | | | | | | X |
| | Crash safety | | | | | | | | | X |
| | Productivity | | X | X | X | X | | | X | X |
| | Homologation | | | | | | | | | X |
| Seat Pad Foam | Material type | X | X | X | | | X | | | X |
| | Product shape | | X | X | | | X | | | X |
| | Product size | | X | X | | | X | | | X |
| | Appearance of product | | X | X | | | X | | | X |
| | Product durability | X | X | X | | | X | | | X |
| | The setting of tolerance and standard of product | X | X | X | | | | | X | X |
| | Product safety (e.g. Robustness) | | | | | | | | | |
| | Ergonomic factor | X | X | X | | | X | | | X |
| | Environmental factor (e.g. Noise and vibration) | | | | | | | | | X |
| | Maintenance factor | X | | | | | | | | X |
| | A Key function of the seat (e.g. Foldable, lever, etc.) | | | | | | | | | |
| | An additional function of the seat (power seat, heater, etc.) | | | | | | | | | |
| | Legislation | X | X | X | | | X | X | | X |
| | Crash safety | X | | | | | | | | X |
| | Productivity | X | X | X | | | X | X | X | X |
| | Homologation | X | | | | | | | | X |
| Seat Trim Covering | Material type | X | X | X | X | X | X | X | X | X |
| | Product Shape | | | X | | X | | | | X |
| | Product size | | | X | | X | | | | X |
| | Appearance of product | X | X | X | X | X | X | | | X |
| | Product durability | X | X | X | X | X | | | | X |
| | The setting of tolerance and standard of product | | X | X | X | X | | | | X |
| | Product safety (e.g. Robustness) | X | | X | X | X | | | X | X |
| | ergonomic factor | | | | | | | | | |

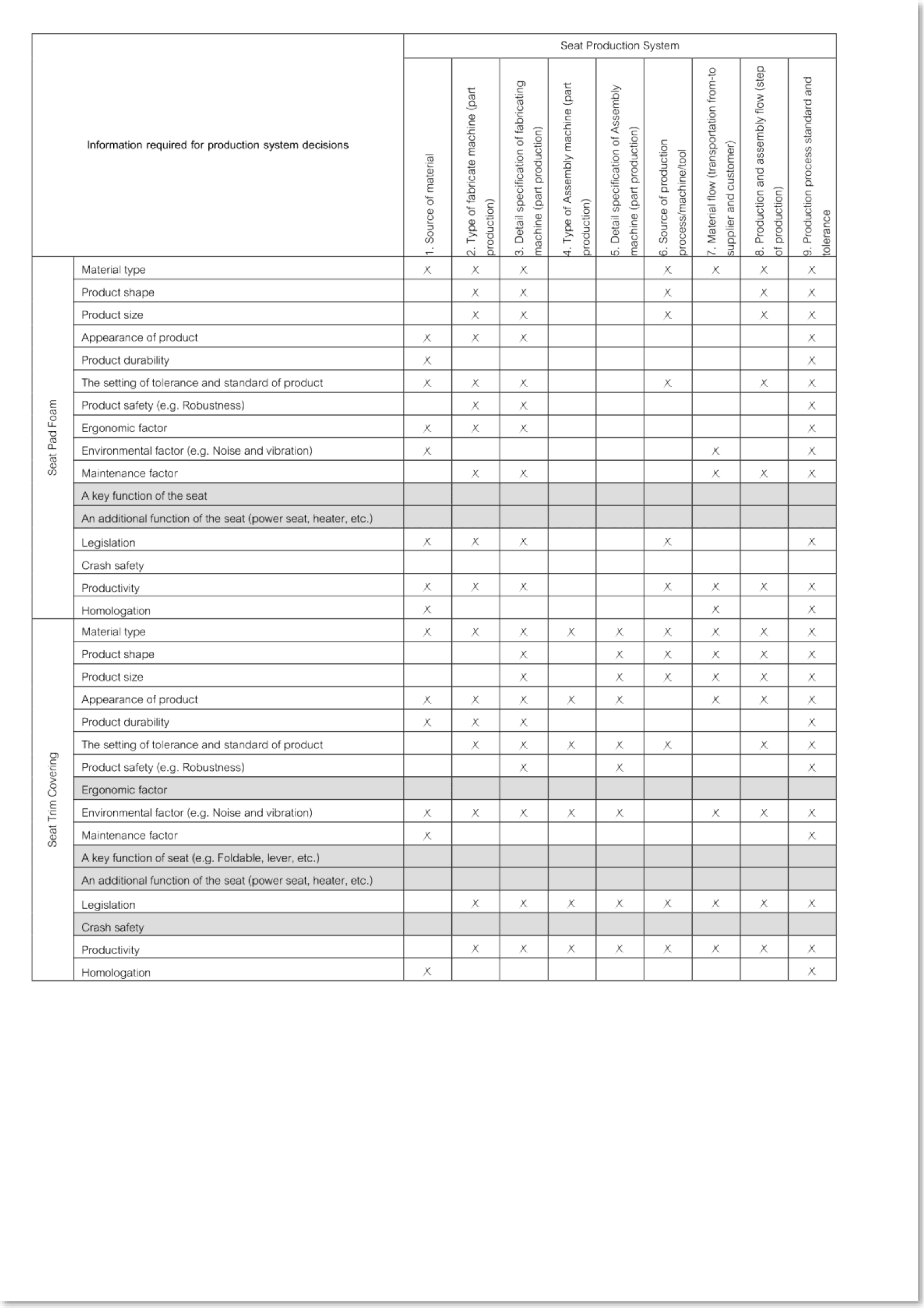


| | Information required for product design decisions | Seat Production System | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 1. Source of material | 2. Type of fabricate machine (part production) | 3. Detail specification of fabricating machine (part production) | 4. Type of Assembly machine (part production) | 5. Detail specification of Assembly machine (part production) | 6. Source of production process/machine/tool | 7. Material flow (transportation from-to supplier and customer) | 8. Production and assembly flow (step of production) | 9. Production process standard and tolerance |
| | Environmental factor (e.g. Noise and vibration) | X | | X | | X | | | X | X |
| | Maintenance factor | X | | X | | X | | | | X |
| | A key function of the seat (e.g. Foldable, lever, etc.) | | | | | | | | | |
| | An additional function of the seat (power seat, heater, etc.) | | | | | | | | | |
| | Legislation | | | X | | X | | | | X |
| | Crash safety | | | | | | | | | |
| | Productivity | | X | X | X | X | | X | X | X |
| | Homologation | | | X | | X | | | | X |

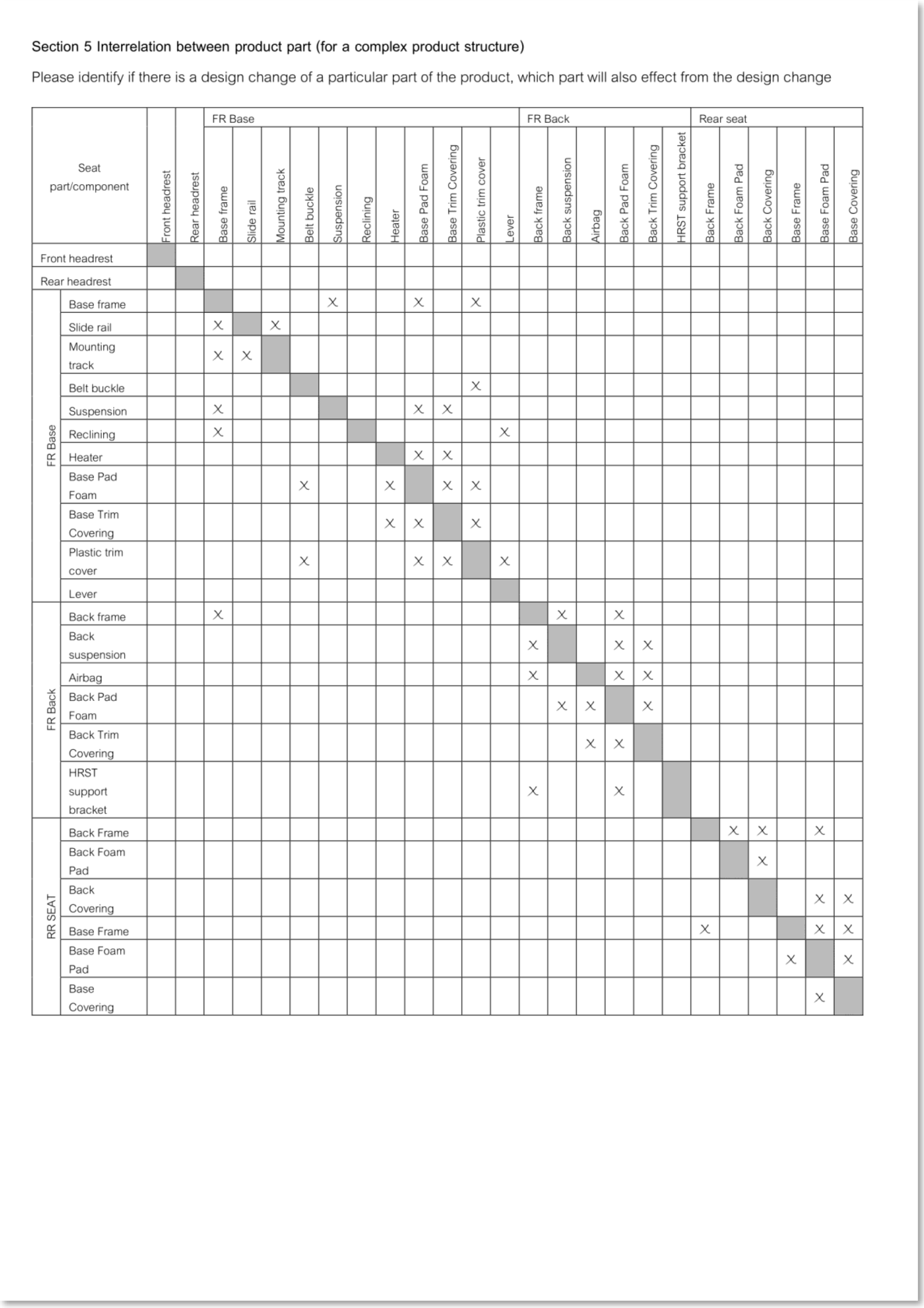
4.2. Based on your experience, which information related to the product is required in order to make production system decisions.

Please put 'x' if the production system information is required.

| | Information required for production system decisions | Seat Production System | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 1. Source of material | 2. Type of fabricate machine (part production) | 3. Detail specification of fabricating machine (part production) | 4. Type of Assembly machine (part production) | 5. Detail specification of Assembly machine (part production) | 6. Source of production process/machine/tool | 7. Material flow (transportation from-to supplier and customer) | 8. Production and assembly flow (step of production) | 9. Production process standard and tolerance |
| Seat Frame | Material type | X | X | X | X | X | X | X | X | X |
| | Product shape | X | X | X | X | X | X | X | X | X |
| | Product size | X | X | X | X | X | X | X | X | X |
| | Appearance of product | | X | X | | | X | | X | X |
| | Product durability | X | X | X | X | X | | | | X |
| | The setting of tolerance and standard of product | X | X | X | | | X | | | X |
| | Product safety (e.g. Robustness) | X | X | X | X | X | | | | X |
| | Ergonomic factor | | | | X | X | | | | X |
| | Environmental factor (e.g. Noise and vibration) | | | | X | X | X | | | X |
| | Maintenance factor | X | X | X | | | | | | X |
| | Key function of the seat (e.g. Foldable, lever, etc.) | | X | X | X | X | X | X | | X |
| | An additional function of the seat (power seat, heater, etc.) | | | | X | X | X | X | | X |
| | Legislation | X | | | | | X | | | X |
| | Crash safety | X | | | X | X | | | | X |
| | Productivity | X | X | X | X | X | X | X | X | |
| | Homologation | X | | | | | | | | X |



| Information required for production system decisions | | Seat Production System | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 1. Source of material | 2. Type of fabricate machine (part production) | 3. Detail specification of fabricating machine (part production) | 4. Type of Assembly machine (part production) | 5. Detail specification of Assembly machine (part production) | 6. Source of production process/machine/tool | 7. Material flow (transportation from-to supplier and customer) | 8. Production and assembly flow (step of production) | 9. Production process standard and tolerance |
| Seat Pad Foam | Material type | X | X | X | | | X | X | X | X |
| | Product shape | | X | X | | | X | | X | X |
| | Product size | | X | X | | | X | | X | X |
| | Appearance of product | X | X | X | | | | | | X |
| | Product durability | X | | | | | | | | X |
| | The setting of tolerance and standard of product | X | X | X | | | X | | X | X |
| | Product safety (e.g. Robustness) | | X | X | | | | | | X |
| | Ergonomic factor | X | X | X | | | | | | X |
| | Environmental factor (e.g. Noise and vibration) | X | | | | | | X | | X |
| | Maintenance factor | | X | X | | | | X | X | X |
| | A key function of the seat | | | | | | | | | |
| | An additional function of the seat (power seat, heater, etc.) | | | | | | | | | |
| | Legislation | X | X | X | | | X | | | X |
| | Crash safety | | | | | | | | | |
| | Productivity | X | X | X | | | X | X | X | X |
| | Homologation | X | | | | | | X | | X |
| Seat Trim Covering | Material type | X | X | X | X | X | X | X | X | X |
| | Product shape | | | X | | X | X | X | X | X |
| | Product size | | | X | | X | X | X | X | X |
| | Appearance of product | X | X | X | X | X | | X | X | X |
| | Product durability | X | X | X | | | | | | X |
| | The setting of tolerance and standard of product | | X | X | X | X | X | | X | X |
| | Product safety (e.g. Robustness) | | | X | | X | | | | X |
| | Ergonomic factor | | | | | | | | | |
| | Environmental factor (e.g. Noise and vibration) | X | X | X | X | X | | X | X | X |
| | Maintenance factor | X | | | | | | | | X |
| | A key function of seat (e.g. Foldable, lever, etc.) | | | | | | | | | |
| | An additional function of the seat (power seat, heater, etc.) | | | | | | | | | |
| | Legislation | | X | X | X | X | X | X | X | X |
| | Crash safety | | | | | | | | | |
| | Productivity | | X | X | X | X | X | X | X | X |
| | Homologation | X | | | | | | | | X |



**Section 5 Interrelation between product part (for a complex product structure)**

Please identify if there is a design change of a particular part of the product, which part will also effect from the design change

| Seat part/component | | Front headrest | Rear headrest | FR Base | | | | | | | | | | | FR Back | | | | | | Rear seat | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Base frame | Slide rail | Mounting track | Belt buckle | Suspension | Reclining | Heater | Base Pad Foam | Base Trim Covering | Plastic trim cover | Lever | Back frame | Back suspension | Airbag | Back Pad Foam | Back Trim Covering | HRST support bracket | Back Frame | Back Foam Pad | Back Covering | Base Frame | Base Foam Pad | Base Covering |
| Front headrest | | ▨ | | | | | | | | | | | | | | | | | | | | | | | | |
| Rear headrest | | | ▨ | | | | | | | | | | | | | | | | | | | | | | | |
| FR Base | Base frame | | | ▨ | | | | X | | | X | | X | | | | | | | | | | | | | |
| | Slide rail | | | X | ▨ | X | | | | | | | | | | | | | | | | | | | | |
| | Mounting track | | | X | X | ▨ | | | | | | | | | | | | | | | | | | | | |
| | Belt buckle | | | | | | ▨ | | | | | | X | | | | | | | | | | | | | |
| | Suspension | | | X | | | | ▨ | | | X | X | | | | | | | | | | | | | | |
| | Reclining | | | X | | | | | ▨ | | | | | X | | | | | | | | | | | | |
| | Heater | | | | | | | | | ▨ | X | X | | | | | | | | | | | | | | |
| | Base Pad Foam | | | | | | X | | | X | ▨ | X | X | | | | | | | | | | | | | |
| | Base Trim Covering | | | | | | | | | X | X | ▨ | X | | | | | | | | | | | | | |
| | Plastic trim cover | | | | | | X | | | | X | X | ▨ | X | | | | | | | | | | | | |
| | Lever | | | | | | | | | | | | | ▨ | | | | | | | | | | | | |
| FR Back | Back frame | | | X | | | | | | | | | | | ▨ | X | | X | | | | | | | | |
| | Back suspension | | | | | | | | | | | | | | X | ▨ | | X | X | | | | | | | |
| | Airbag | | | | | | | | | | | | | | X | | ▨ | X | X | | | | | | | |
| | Back Pad Foam | | | | | | | | | | | | | | | X | X | ▨ | X | | | | | | | |
| | Back Trim Covering | | | | | | | | | | | | | | | | X | X | ▨ | | | | | | | |
| | HRST support bracket | | | | | | | | | | | | | | X | | | X | | ▨ | | | | | | |
| RR SEAT | Back Frame | | | | | | | | | | | | | | | | | | | | ▨ | X | X | | X | |
| | Back Foam Pad | | | | | | | | | | | | | | | | | | | | | ▨ | X | | | |
| | Back Covering | | | | | | | | | | | | | | | | | | | | | | ▨ | | X | X |
| | Base Frame | | | | | | | | | | | | | | | | | | | | X | | | ▨ | X | X |
| | Base Foam Pad | | | | | | | | | | | | | | | | | | | | | | | X | ▨ | X |
| | Base Covering | | | | | | | | | | | | | | | | | | | | | | | | X | ▨ |

## A4.2 Data support resource consumption assessment

| No. | Part Level | Part name | Component | Component type | Material | Weight (kg) | Model A | | Model B | | Material | Model C | | Model D | | Model E | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Number / carset | Weight/carset (kg) | Number / carset | Weight/carset (kg) | | Number / carset | Weight/carset (kg) | Number / carset | Weight/carset (kg) | Number / carset | Weight/carset (kg) |
| | 1 | FR Headrest | | Standard | | | | 1.89 | | 1.89 | | | 1.494 | | 1.494 | | 1.494 |
| 1 | 2 | | HRST covering | **Standard w/option** | Leather | 0.396 | 2 | 0.792 | 2 | 0.792 | Fabric | 2 | 0.396 | 2 | 0.396 | 2 | 0.396 |
| 2 | 2 | | HRST Pad | Standard | PU | 0.221 | 2 | 0.442 | 2 | 0.442 | PU | 2 | 0.442 | 2 | 0.442 | 2 | 0.442 |
| 3 | 2 | | HRST frame | Standard | Steel+coating | 0.328 | 2 | 0.656 | 2 | 0.656 | Steel+coating | 2 | 0.656 | 2 | 0.656 | 2 | 0.656 |
| | 1 | RR Headrest | | Standard | | | | 2.835 | | 1.89 | | | 0 | | 0 | | 0 |
| 4 | 2 | | HRST covering | **Standard w/option 2-3 fix/adjust** | Leather | 0.396 | 3 | 1.188 | 2 | 0.792 | Fabric | 0 | 0 | 0 | 0 | 0 | 0 |
| 5 | 2 | | HRST Pad | **Standard w/option 2-3 fix/adjust** | PU | 0.221 | 3 | 0.663 | 2 | 0.442 | PU | 0 | 0 | 0 | 0 | 0 | 0 |
| 6 | 2 | | HRST frame | **Standard w/option 2-3 fix/adjust** | Steel+coating | 0.328 | 3 | 0.984 | 2 | 0.656 | Steel+coating | 0 | 0 | 0 | 0 | 0 | 0 |
| | 1 | Front seat left-hand side | | Standard | | | | 23.483 | | 23.16 | | | 22.224 | | 21.901 | | 21.235 |
| | 2 | FR LH Base | | Standard | - | | | 16.165 | | 15.842 | - | | 15.719 | | 15.396 | | 15.396 |
| 7 | 3 | | Base frame | Standard | Steel | 3.5 | 1 | 3.5 | 1 | 3.5 | Steel | 1 | 3.5 | 1 | 3.5 | 1 | 3.5 |
| 8 | 4 | | Slide rail | Standard | Steel | 2 | 1 | 2 | 1 | 2 | Steel | 1 | 2 | 1 | 2 | 1 | 2 |
| 9 | 4 | | Mounting track | Standard | Steel | 5.312 | 1 | 5.312 | 1 | 5.312 | Steel | 1 | 5.312 | 1 | 5.312 | 1 | 5.312 |
| 10 | 4 | | Belt buckle | Standard | Mix | 0.05 | 1 | 0.05 | 1 | 0.05 | Mix | 1 | 0.05 | 1 | 0.05 | 1 | 0.05 |
| 11 | 4 | | Suspension | Standard | Steel | 0.341 | 1 | 0.341 | 1 | 0.341 | Steel | 1 | 0.341 | 1 | 0.341 | 1 | 0.341 |
| 12 | 4 | | Reclining | Standard | Mix | 2.278 | 1 | 2.278 | 1 | 2.278 | Mix | 1 | 2.278 | 1 | 2.278 | 1 | 2.278 |
| 13 | 4 | | Heater | **Option** | Mix | 0.193 | 1 | 0.193 | 0 | 0 | Mix | 1 | 0.193 | 0 | 0 | 0 | 0 |
| 14 | 3 | | Base Pad foam | Standard | PU | 0.863 | 1 | 0.863 | 1 | 0.863 | PU | 1 | 0.863 | 1 | 0.863 | 1 | 0.863 |
| | 3 | | Base Trim Covering | Standard | - | 0.892 | 1 | 0.892 | 1 | 0.892 | - | 1 | 0.446 | 1 | 0.446 | 1 | 0.446 |
| 15 | 4 | | laminated foam | Standard | Graphite foam | 0 | 1 | 0 | 1 | 0 | Graphite foam | 1 | 0 | 1 | 0 | 1 | 0 |
| 16 | 4 | | cover | **Standard w/option** | Leather | 0 | 1 | 0 | 1 | 0 | Fabric | 1 | 0 | 1 | 0 | 1 | 0 |
| 17 | 4 | | trim rod | Standard | Plastic | 0 | 1 | 0 | 1 | 0 | Plastic | 1 | 0 | 1 | 0 | 1 | 0 |
| 18 | 3 | | Plastic trim cover | Standard | Plastic | 0.606 | 1 | 0.606 | 1 | 0.606 | Plastic | 1 | 0.606 | 1 | 0.606 | 1 | 0.606 |
| 19 | 3 | | Lever | **Option** | Mix | 0.13 | 1 | 0.13 | 0 | 0 | Mix | 1 | 0.13 | 0 | 0 | 0 | 0 |
| | 2 | FR LH Back | | Standard | | | | 7.318 | | 7.318 | | | 6.505 | | 6.505 | | 5.839 |
| 20 | 3 | | Back frame | Standard | Steel | 3.8 | 1 | 3.8 | 1 | 3.8 | Steel | 1 | 3.8 | 1 | 3.8 | 1 | 3.8 |
| 21 | 3 | | Back suspension | Standard | Steel | 0.046 | 1 | 0.046 | 1 | 0.046 | Steel | 1 | 0.046 | 1 | 0.046 | 1 | 0.046 |
| 22 | 3 | | Airbag | **Option** | Mix | 0.666 | 1 | 0.666 | 1 | 0.666 | Mix | 1 | 0.666 | 1 | 0.666 | 0 | 0 |
| 23 | 3 | | Back Pad foam | Standard | PU | 1.11 | 1 | 1.11 | 1 | 1.11 | PU | 1 | 1.11 | 1 | 1.11 | 1 | 1.11 |
| | 3 | | Back Trim Covering | Standard | - | 1.626 | 1 | 1.626 | 1 | 1.626 | - | 1 | 0.813 | 1 | 0.813 | 1 | 0.813 |
| 24 | 4 | | laminated foam | Standard | Graphite foam | 0 | 1 | 0 | 1 | 0 | Graphite foam | 1 | 0 | 1 | 0 | 1 | 0 |
| 25 | 4 | | cover | **Standard w/option** | Leather | 0 | 1 | 0 | 1 | 0 | Fabric | 1 | 0 | 1 | 0 | 1 | 0 |
| 26 | 4 | | trim rod | Standard | Plastic | 0 | 1 | 0 | 1 | 0 | Plastic | 1 | 0 | 1 | 0 | 1 | 0 |
| 27 | 3 | | HRST support brck | Standard | Plastic | 0.035 | 2 | 0.07 | 2 | 0.07 | Plastic | 2 | 0.07 | 2 | 0.07 | 2 | 0.07 |

# A4.3 Data supporting resource consumption assessment (continue)

| No. | Part Level | Part name | Component | Component type | Material | Weight (kg) | Model A |  | Model B |  | Material | Model C |  | Model D |  | Model E |  |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  |  |  |  |  |  |  | Number / carset | Weight/carset (kg) | Number / carset | Weight/carset (kg) |  | Number / carset | Weight/carset (kg) | Number / carset | Weight/carset (kg) | Number / carset | Weight/carset (kg) |
|  | 1 | Front seat right-hand side |  | Standard |  |  |  | 23.483 |  | 23.16 |  |  | 22.224 |  | 21.901 |  | 21.235 |
|  | 2 | FR RH Base |  | Standard | - |  |  | 16.165 |  | 15.842 | - |  | 15.719 |  | 15.396 |  | 15.396 |
| 28 | 3 |  | Base frame | Standard | Steel | 3.5 | 1 | 3.5 | 1 | 3.5 | Steel | 1 | 3.5 | 1 | 3.5 | 1 | 3.5 |
| 29 | 4 |  | Slide rail | Standard | Steel | 2 | 1 | 2 | 1 | 2 | Steel | 1 | 2 | 1 | 2 | 1 | 2 |
| 30 | 4 |  | Mounting track | Standard | Steel | 5.312 | 1 | 5.312 | 1 | 5.312 | Steel | 1 | 5.312 | 1 | 5.312 | 1 | 5.312 |
| 31 | 4 |  | Belt receptacle | Standard | Mix | 0.05 | 1 | 0.05 | 1 | 0.05 | Mix | 1 | 0.05 | 1 | 0.05 | 1 | 0.05 |
| 32 | 4 |  | Suspension | Standard | Steel | 0.341 | 1 | 0.341 | 1 | 0.341 | Steel | 1 | 0.341 | 1 | 0.341 | 1 | 0.341 |
| 33 | 4 |  | Reclining | Standard | Mix | 2.278 | 1 | 2.278 | 1 | 2.278 | Mix | 1 | 2.278 | 1 | 2.278 | 1 | 2.278 |
| 34 | 4 |  | Heater | **Option** | Mix | 0.193 | 1 | 0.193 | 0 | 0 | Mix | 1 | 0.193 | 0 | 0 | 0 | 0 |
| 35 | 3 |  | Base Pad foam | Standard | PU | 0.863 | 1 | 0.863 | 1 | 0.863 | PU | 1 | 0.863 | 1 | 0.863 | 1 | 0.863 |
|  | 3 |  | Base Trim Covering | Standard | - | 0.892 | 1 | 0.892 | 1 | 0.892 | - | 1 | 0.446 | 1 | 0.446 | 1 | 0.446 |
| 36 | 4 |  | laminated foam | Standard | Graphite foam | 0 | 1 | 0 | 1 | 0 | Graphite foam | 1 | 0 | 1 | 0 | 1 | 0 |
| 37 | 4 |  | cover | **Standard w/option** | Leather | 0 | 1 | 0 | 1 | 0 | Fabric | 1 | 0 | 1 | 0 | 1 | 0 |
| 38 | 4 |  | trim rod | Standard | Plastic | 0 | 1 | 0 | 1 | 0 | Plastic | 1 | 0 | 1 | 0 | 1 | 0 |
| 39 | 3 |  | Plastic trim cover | Standard | Plastic | 0.606 | 1 | 0.606 | 1 | 0.606 | Plastic | 1 | 0.606 | 1 | 0.606 | 1 | 0.606 |
| 40 | 3 |  | Lever | **Option** | Mix | 0.13 | 1 | 0.13 | 0 | 0 | Mix | 1 | 0.13 | 0 | 0 | 0 | 0 |
|  | 2 | FR RH Back |  | Standard | - |  |  | 7.318 |  | 7.318 | - |  | 6.505 |  | 6.505 |  | 5.839 |
| 41 | 3 |  | Back frame | Standard | Steel | 3.8 | 1 | 3.8 | 1 | 3.8 | Steel | 1 | 3.8 | 1 | 3.8 | 1 | 3.8 |
| 42 | 4 |  | Back suspension | Standard | Steel | 0.046 | 1 | 0.046 | 1 | 0.046 | Steel | 1 | 0.046 | 1 | 0.046 | 1 | 0.046 |
| 43 | 4 |  | Airbag | **Option** | Mix | 0.666 | 1 | 0.666 | 1 | 0.666 | Mix | 1 | 0.666 | 1 | 0.666 | 0 | 0 |
| 44 | 3 |  | Back Pad foam | Standard | PU | 1.11 | 1 | 1.11 | 1 | 1.11 | PU | 1 | 1.11 | 1 | 1.11 | 1 | 1.11 |
|  | 3 |  | Back Trim Covering | Standard | - | 1.626 | 1 | 1.626 | 1 | 1.626 | - | 1 | 0.813 | 1 | 0.813 | 1 | 0.813 |
| 45 | 4 |  | laminated foam | Standard | Graphite foam | 0 | 1 | 0 | 1 | 0 | Graphite foam | 1 | 0 | 1 | 0 | 1 | 0 |
| 46 | 4 |  | cover | **Standard w/option** | Leather | 0 | 1 | 0 | 1 | 0 | Fabric | 1 | 0 | 1 | 0 | 1 | 0 |
| 47 | 4 |  | trim rod | Standard | Plastic | 0 | 1 | 0 | 1 | 0 | Plastic | 1 | 0 | 1 | 0 | 1 | 0 |
| 48 | 3 |  | HRST support brck | Standard | Plastic | 0.035 | 2 | 0.07 | 2 | 0.07 | Plastic | 2 | 0.07 | 2 | 0.07 | 2 | 0.07 |
|  | 1 | RR SEAT |  |  |  |  |  | 21.5415 |  | 21.5415 |  |  | 20.912 |  | 20.912 |  | 20.912 |
|  | 2 | RR Back |  |  | - |  |  |  |  |  | - |  |  |  |  |  |  |
| 49 | 3 |  | RR Back Frame | Standard | Steel | 7.6 | 1 | 7.6 | 1 | 7.6 | Steel | 1 | 7.6 | 1 | 7.6 | 1 | 7.6 |
| 50 | 3 |  | RR Back Foam Pad | Standard | PU | 3.885 | 1 | 3.885 | 1 | 3.885 | PU | 1 | 3.885 | 1 | 3.885 | 1 | 3.885 |
|  | 3 |  | RR Back Covering | Standard | - | 3.252 | 1 | 3.252 | 1 | 3.252 | - | 1 | 2.8455 | 1 | 2.8455 | 1 | 2.8455 |
| 51 | 4 |  | laminated foam | Standard | Graphite foam | 0 | 1 | 0 | 1 | 0 | Graphite foam | 1 | 0 | 1 | 0 | 1 | 0 |
| 52 | 4 |  | cover | **Standard w/option** | Leather | 0 | 1 | 0 | 1 | 0 | Fabric | 1 | 0 | 1 | 0 | 1 | 0 |
| 53 | 4 |  | trim rod | Standard | Plastic | 0 | 1 | 0 | 1 | 0 | Plastic | 1 | 0 | 1 | 0 | 1 | 0 |
|  | 2 | RR Base |  |  | - |  | 1 | 0 | 1 | 0 | - | 1 | 0 | 1 | 0 | 1 | 0 |
| 54 | 3 |  | RR Base Frame | Standard | Steel | 2 | 1 | 2 | 1 | 2 | Steel | 1 | 2 | 1 | 2 | 1 | 2 |
| 55 | 3 |  | RR Base Foam Pad | Standard | PU | 3.0205 | 1 | 3.0205 | 1 | 3.0205 | PU | 1 | 3.0205 | 1 | 3.0205 | 1 | 3.0205 |
|  | 3 |  | RR Base Covering | Standard | - | 1.784 | 1 | 1.784 | 1 | 1.784 | - | 1 | 1.561 | 1 | 1.561 | 1 | 1.561 |
| 56 | 4 |  | laminated foam | Standard | Graphite foam | 0 | 1 | 0 | 1 | 0 | Graphite foam | 1 | 0 | 1 | 0 | 1 | 0 |
| 57 | 4 |  | cover | **Standard w/option** | Leather | 0 | 1 | 0 | 1 | 0 | Fabric | 1 | 0 | 1 | 0 | 1 | 0 |
| 58 | 4 |  | trim rod | Standard | Plastic | 0 | 1 | 0 | 1 | 0 | Plastic | 1 | 0 | 1 | 0 | 1 | 0 |
|  |  |  |  |  |  |  | Total | 73.2325 | Total | 71.6415 |  | Total | 66.854 | Total | 66.208 | Total | 64.876 |

## A4.3 The complete calculation of resource consumption assessment

| No. | Production system | Process | **Part name** | **Component** | **Material** | Material (Kg/annual) | | | | | | | Energy (kW/annual) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Input | | Output | Reject rate | Waste | | | TE | AE | DE | IE | EPE | ER |
| 1 | Seat Frame Production | | | | | | | | | | | | | | | | | |
| | | Bending | FR Base | Slide rail | Steel | 462,279 | 1,788,061 | 411428.57 | 11% | 50,851 | 204,267 | 11.42% | 499,200.00 | 42,000.00 | 541,200.00 | 208,101 | 749,301 | 0.92 |
| | | | FR Base | Mounting track | Steel | 1,241,766 | | 1092754.3 | 12% | 149,012 | | | | | | | | |
| system+A2:S43 | | | FR Base | Suspension | Steel | 73,841 | | 70148.571 | 5% | 3,692 | | | | | | | | |
| | | | FR Back | Back suspension | Steel | 10,175 | | 9462.8571 | 7% | 712 | | | | | | | | |
| | | Stamping | FR Base | Base frame | Steel | 776,273 | 1,984,739 | 706408.16 | 9% | 69,865 | 204,157 | 10.29% | 480,000.00 | 342,000.00 | 822,000.00 | 208,101 | 1,030,101 | 0.58 |
| | | | FR Base | Reclining | Steel | 332,391 | | 285856.46 | 14% | 46,535 | | | | | | | | |
| | | | FR Back | Back frame | Steel | 868,571 | | 781714.29 | 10% | 86,857 | | | | | | | | |
| | | | FR Base | Lever | Steel | 7,503 | | 6602.9388 | 12% | 900 | | | | | | | | |
| | | Welding | | | | | | | | | | | 192,000.00 | 86,400.00 | 278,400.00 | 208,101 | 486,501 | 0.69 |
| | | Assembly (airgun, bolt, screw) | | Bolt,screw,knot | | | | | | | | | 13,430.00 | 8,326.60 | 21,756.60 | 208,101 | 229,858 | 0.62 |
| | | | | | | | | | | | | | | | | | | |
| 2 | Seat Pad Foam Production | | | | | | | | | | | | | | | | | |
| | | Mould spraying | | | | | | | | | | | - | - | - | - | - | - |
| | | Foam injection | FR Base | Base Pad foam | PU | 197,257 | 450,971 | 177,531 | 10% | 19,726 | 45,097 | 10.00% | 520,000.00 | 357,500.00 | 877,500.00 | 832,405 | 1,709,905 | 0.59 |
| | | | FR Back | Back Pad foam | PU | 253,714 | | 228,343 | 10% | 25,371 | | | | | | | | |
| | | | | | | | | | | | | | | | | | | |
| 3 | Seat Covering - Leather | | | | | | | | | | | | | | | | | |
| | | Crusting (Dyeing, Softening, Drying) | FR Base | Base Trim Covering | - | | | 80,794 | | | | | 39,000 | 23,010 | 62,010 | 104,051 | 166,061 | 0.63 |
| | | Cutting | | laminated foam | Graphite foam | 19,949 | | 16,159 | 19% | 3,790 | | | 96,000 | 33,600 | 129,600 | 104,051 | 233,651 | 0.74 |
| | | Lamination | | cover | Leather | 65,156 | | 40,397 | 38% | 24,759 | | | 15,600 | 4,368 | 19,968 | 104,051 | 124,019 | 0.78 |
| | | Sawing | | trim rod | Nylon | 25,514 | | 24,238 | 5% | 1,276 | | | 15,600 | 4,368 | 19,968 | 104,051 | 124,019 | 0.78 |
| | | - | FR Back | Back Trim Covering | - | | | 147,277 | | 0 | | | - | - | - | - | - | - |
| | | - | | laminated foam | Graphite foam | 34,250 | | 29,455 | 14% | 4,795 | | | - | - | - | - | - | - |
| | | - | | cover | Leather | 100,874 | | 73,638 | 27% | 27,236 | | | - | - | - | - | - | - |
| | | - | | trim rod | Nylon | 46,508 | | 44,183 | 5% | 2,325 | | | - | - | - | - | - | - |
| | | - | RR Back | RR Back Covering | - | | | 151,988 | | 0 | | | - | - | - | - | - | - |
| | | - | | laminated foam | Graphite foam | 36,624 | | 30,398 | 17% | 6,226 | | | - | - | - | - | - | - |
| | | - | | cover | Leather | 116,914 | | 75,994 | 35% | 40,920 | | | - | - | - | - | - | - |
| | | - | | trim rod | Nylon | 47,996 | | 45,596 | 5% | 2,400 | | | - | - | - | - | - | - |
| | | - | RR Base | RR Base Covering | - | | | 83,379 | | 0 | | | - | - | - | - | - | - |
| | | - | | laminated foam | Graphite foam | 20,336 | 111,159 | 16,676 | 18% | 3,661 | 18,472 | 16.62% | - | - | - | - | - | - |
| | | - | | cover | Leather | 66,173 | 349,118 | 41,689 | 37% | 24,484 | 117,400 | 33.63% | - | - | - | - | - | - |
| | | - | | trim rod | Nylon | 26,330 | 146,349 | 25,014 | 5% | 1,317 | 7,317 | 5.00% | - | - | - | - | - | - |

## A4.3 The complete calculation of resource consumption assessment (continue)

| No. | Production system | Process | **Part name** | **Component** | **Material** | Material (Kg/annual) | | | | | | | Energy (kW/annual) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Input | | Output | Reject rate | Waste | | | TE | AE | DE | IE | EPE | ER |
| 4 | Seat Covering - Fabric | Fabic praparation | FR Base | Base Trim Covering | - | | | **51,315** | | 0 | | | 2,232,333 | 1,004,550 | 3,236,883 | 104,051 | 3,340,933 | 0.69 |
| | | Cutting | | laminated foam | Graphite foam | 12,074 | | 10,263 | 15% | 1,811 | | | 96,000 | 33,600 | 129,600 | 104,051 | 233,651 | 0.74 |
| | | Lamination | | cover | Fabric | 36,864 | | 25,657 | 30% | 11,207 | | | 14,040 | 3,931 | 17,971 | 104,051 | 122,022 | 0.78 |
| | | Sawing | | trim rod | Nylon | 16,205 | | 15,394 | 5% | 810 | | | 14,040 | 3,931 | 17,971 | 104,051 | 122,022 | 0.78 |
| | | - | FR LBack | Back Trim Covering | - | | | **93,541** | | 0 | | | - | - | - | - | - | - |
| | | - | | laminated foam | Graphite foam | 21,020 | | 18,708 | 11% | 2,312 | | | - | - | - | - | - | - |
| | | - | | cover | Fabric | 596,559 | | 467,703 | 22% | 128,857 | | | - | - | - | - | - | - |
| | | - | | trim rod | Nylon | 29,539 | | 28,062 | 5% | 1,477 | | | - | - | - | - | - | - |
| | | - | RR Back | RR Back Covering | - | | | 92,674 | | 0 | | | - | - | - | - | - | - |
| | | - | | laminated foam | Graphite foam | 21,552 | | 18,535 | 14% | 3,017 | | | - | - | - | - | - | - |
| | | - | | cover | Fabric | 64,357 | | 46,337 | 28% | 18,020 | | | - | - | - | - | - | - |
| | | - | | trim rod | Nylon | 29,266 | | 27,802 | 5% | 1,463 | | | - | - | - | - | - | - |
| | | - | RR Base | RR Base Covering | - | | | 168,935 | | 0 | | | - | - | - | - | - | - |
| | | - | | laminated foam | Graphite foam | 39,749 | 94,396 | 33,787 | 15% | 5,962 | 13,103 | 13.88% | - | - | - | - | - | - |
| | | - | | cover | Fabric | 71,989 | 769,770 | 50,680 | 30% | 21,309 | 179,392 | 23.30% | - | - | - | - | - | - |
| | | - | | trim rod | Nylon | 88,913 | 163,922 | 84,467 | 5% | 4,446 | 8,196 | 5.00% | - | - | - | - | - | - |
| | | | | | | | | | | | | | | | | | | |
| 5 | Plastic Part Production | Plastic Injection | | | | | | | | | | | 435,840 | 196,128 | 631,968 | 416,202 | 1,048,170 | 0.69 |
| | | Laser triming | FR Base | Reclining | Polypropylene | 196,517 | 488,745 | 182,761 | 7% | 13,756 | 33,108 | 7% | 28,800 | 12,960 | 41,760 | 416,202 | 457,962 | 0.69 |
| | | | FR Base | Lever | Polypropylene | 4,491 | | 4,222 | 6% | 269 | | | | | | | | |
| | | | FR Base | Plastic trim cover | Polypropylene | 131,224 | | 124,663 | 5% | 6,561 | | | | | | | | |
| | | | FR Back | HRST support brck | Polypropylene | 156,513 | | 143,992 | 8% | 12,521 | | | | | | | | |
| | | | | | | | | | | | | | | | | | | |
| 6 | **HRST Production** | HRST frame bending | FR Headrest | HRST frame | Steel | 71,693 | 110,527 | 66,125 | 8% | 5,568 | 8,585 | 7.77% | 124,800 | 67,200 | 192,000 | **208,101** | **400,101** | 0.65 |
| | | | RR Headrest | HRST frame | Steel | 38,834 | | 35,818 | 8% | 3,016 | | | | | | | | |
| | | HRST frame coating | | | Chrome | 0 | | | 5% | 0 | | | 470,400 | 319,872 | 790,272 | 208,101 | 998,373 | 0.60 |
| | | | | | Zinc | 0 | | | 5% | 0 | | | | | | | | |
| | | L-HRST Mould preparation | | | Chemical A | 0 | | | 5% | 0 | | | 156,000.00 | 107,250.00 | 263,250.00 | 208,101 | 471,351 | 0.59 |
| | | L-Foam injection | FR Headrest | HRST Pad | PUR | 21,277 | | 19,625 | 8% | 1,653 | | | | | | | | |
| | | L-Pressing | RR Headrest | HRST Pad | PUR | 26,674 | | 24,133 | 10% | 2,540 | | | | | | | | |
| | | | FR Headrest | HRST covering | Leather | 44,419 | 101,318 | 35,165 | 25% | 9,254 | 22,910 | 22.61% | | | | | | |
| | | | RR Headrest | HRST covering | Leather | 56,899 | | 43,243 | 30% | 13,656 | | | | | | | | |
| | | | - | - | - | 0 | | | 5% | 0 | | | | | | | | |
| | | F-HRST Mould preparation | | | Chameical B | 0 | | | 5% | 0 | | | 156,000.00 | 107,250.00 | 263,250.00 | 208,101 | 471,351 | 0.59 |
| | | F-Foam injection | FR Headrest | HRST Pad | PU | 26,761 | | 24,924 | 7% | 1,837 | | | | | | | | |
| | | | RR Headrest | HRST Pad | PU | 0 | 74,711 | 0 | 0% | 0 | 6,029 | 8.07% | | | | | | |
| | | F-Pressing | - | - | - | 0 | | | | 0 | | | | | | | | |
| | | F-Covering | FR Headrest | HRST covering | Fabric | 23,510 | 23,510 | 22,334 | 5% | 1,175 | 1,175 | 5.00% | | | | | | |
| | | | RR Headrest | HRST covering | Fabric | 0 | | 0 | 0% | | | | | | | | | |
| | | | | | | | | | | | | | | | | | | |

## A4.3 The complete calculation of resource consumption assessment (continue)

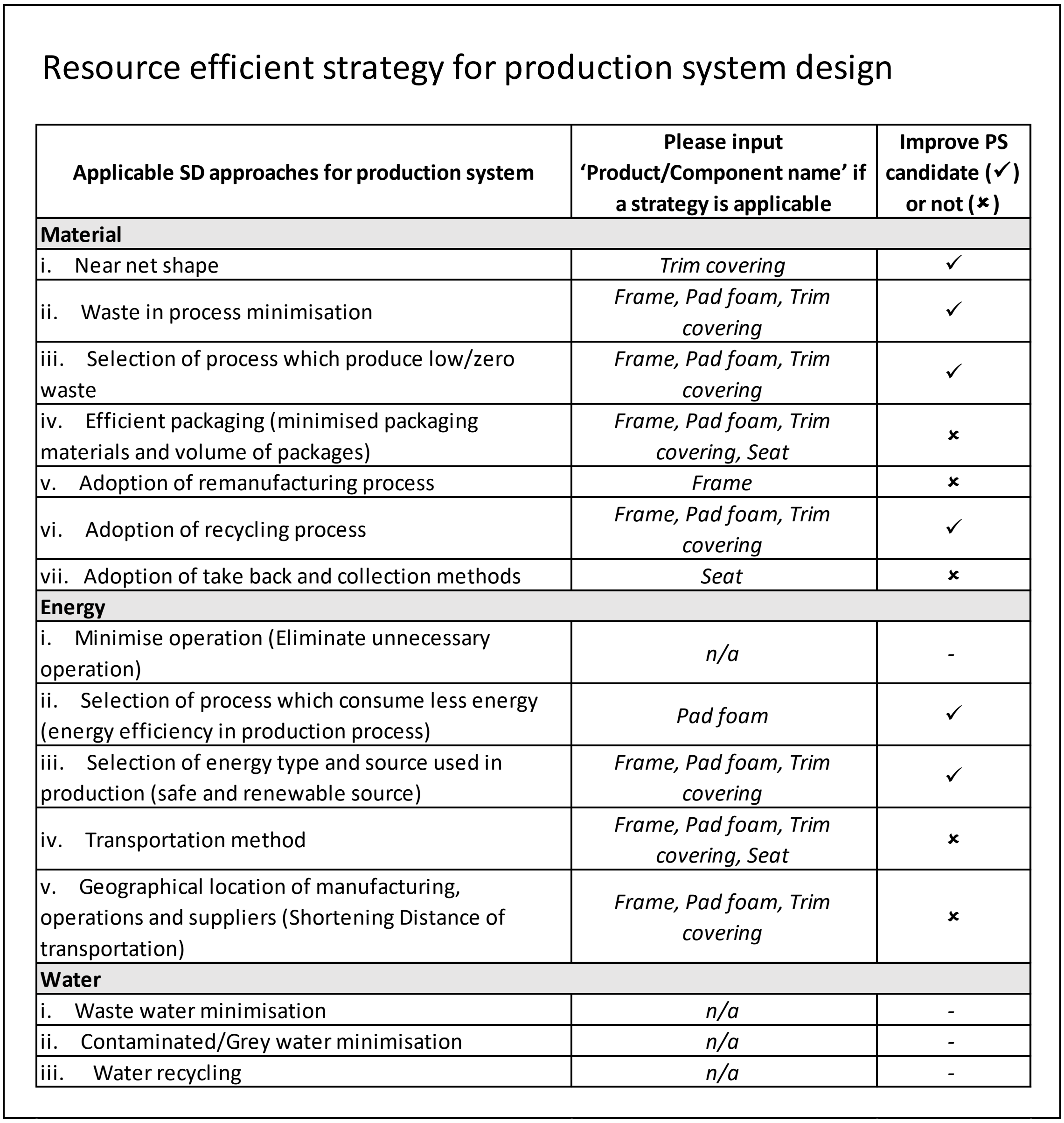
| No. | Production system | Process | **Part name** | **Component** | **Material** | Material (Kg/annual) | | | | | | | Energy (kW/annual) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Input | | Output | Reject rate | Waste | | | TE | AE | DE | IE | EPE | ER |
| 7 | Front Seat production | | | | | | | | | | | | | | | | | |
| | | Seat Frame assembly | FR Base | Base frame | Steel | 706,408 | | 692,280 | 2% | 14,128 | | | 3,223,200 | 2,095,080 | 5,318,280 | 416,202 | 5,734,482 | 0.61 |
| | | 2set *3 conveyor*6days | FR Base | Slide rail | Steel | 411,429 | | 403,200 | 2% | 8,229 | | | | | | | | |
| | | air gun system | FR Base | Mounting track | Steel | 1,092,754 | | 1,070,899 | 2% | 21,855 | | | | | | | | |
| | | | FR Base | Belt buckle | Mix | 10,080 | | 10,080 | - | | | | | | | | | |
| | | | FR Base | Suspension | Steel | 70,149 | | 68,746 | 2% | 1,403 | | | | | | | | |
| | | | FR Base | Reclining | Mix | 468,617 | | 459,245 | 2% | 9,372 | | | | | | | | |
| | | | FR Base | Heater | Mix | 16,070 | | 15,749 | 2% | 321 | | | | | | | | |
| | | | FR Base | Lever | Mix | 10,824 | | 10,608 | 2% | 216 | | | | | | | | |
| | | | FR Back | Back frame | Steel | 781,714 | | 766,080 | 2% | 15,634 | | | | | | | | |
| | | | FR Back | Back suspension | Steel | 9,463 | 3,071,917 | 9,274 | 2% | 189 | 61,438 | 2.00% | | | | | | |
| | | | FR Back | Airbag | Mix | 119,880 | | 119,880 | - | | | | | | | | | |
| | | Foam pad assembly | FR Base | Base Pad foam | PU | 177,531 | | 173,981 | 2% | 3,551 | | | 64,800 | 16,200 | 81,000 | 416,202 | 497,202 | 0.80 |
| | | | FR Back | Back Pad foam | PU | 228,343 | 405,874 | 223,776 | 2% | 4,567 | 8,117 | 2.00% | | | | | | |
| | | Leather covering assembly | FR Base | Base Trim Covering | Leather | 80,826 | | 79,210 | 2% | 1,617 | | | | | | | | |
| | | | FR Back | Back Trim Covering | Leather | 147,336 | 228,162 | 144,389 | 2% | 2,947 | 4,563 | 2.00% | | | | | | |
| | | Fabric covering assembly | FR Base | Base Trim Covering | Fabric | 51,336 | | 50,309 | 2% | 1,027 | | | | | | | | |
| | | | FR Back | Back Trim Covering | Fabric | 93,578 | 144,913 | 91,706 | 2% | 1,872 | 2,898 | 2.00% | | | | | | |
| | | Injection part assembly | FR Base | Plastic trim cover | Polypropylene | 124,663 | | 122,170 | 2% | 2,493 | | | | | | | | |
| | | | FR Back | HRST support brck | Polypropylene | 143,992 | 268,655 | 141,112 | 2% | 2,880 | 5,373 | 2.00% | | | | | | |
| | | Head rest assembly | | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | | | |
| 8 | Rear Seat production | | | | | | | | | | | | | | | | | |
| | | Frame welding | RR Base | RR Base Frame | Steel | 212,211 | 1,018,611 | 201,600 | 5% | 10,611 | 50,931 | 5% | 192,000 | 86,400 | 278,400 | 277,468 | 555,868 | 0.69 |
| | | | RR Back | RR Back Frame | Steel | 806,400 | | 766,080 | 5% | 40,320 | | | | | | | | |
| | | Foam injection | RR Base | RR Base Foam Pad | PU | 320,491 | 732,710 | 304,466 | 5% | 16,025 | 36,635 | 5% | 260,000 | 145,600 | 405,600 | 277,468 | 683,068 | 0.64 |
| | | | RR Back | RR Back Foam Pad | PU | 412,219 | | 391,608 | 5% | 20,611 | | | | | | | | |
| | | Foam pressing | | | | | | | | | | | - | - | - | | | |
| | | Leather covering assembly | RR Base | RR Base Covering | Leather | 151,988 | 235,367 | 144,389 | 5% | 7,599 | 11,768 | 5.00% | 28,800 | 7,200 | 36,000 | 277,468 | 313,468 | 0.80 |
| | | | RR Back | RR Back Covering | Leather | 83,379 | | 79,210 | 5% | 4,169 | | | | | | | | |
| | | Fabric covering assembly | RR Base | RR BaseCovering | Fabric | 92,674 | 261,609 | 88,040 | 5% | 4,634 | 13,080 | 5.00% | | | | | | |
| | | | RR Back | RR Back Covering | Fabric | 168,935 | | 160,488 | 5% | 8,447 | | | | | | | | |
| | | Head rest assembly | | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | 14,476,607.63 | 6,659,240 | | |

## A4.4 Checklist for selecting resource efficient design strategy for product design

### Resource efficient design strategy for product design

| **Applicable strategies for product** | | **Please input 'Product/Component name' if a strategy is applicable** | **Improve PS candidate (✓) or not (×)** |
|---|---|---|---|
| **Material** | Material Elimination | | |
| | i. Dematerialise product service | *n/a* | - |
| | ii. Consolidate material variety (Homogenous material/Sta | *Frame, Pad foam, Trim covering* | ✓ |
| | Material Minimisation | | |
| | i. Restructuring product | *Frame, Pad foam, Trim covering* | ✓ |
| | ii. Size reduction (near net shape) | *Frame, Pad foam, Trim covering* | ✓ |
| | iii. Light weighting | *Frame* | × |
| | iv. Optimise quantity of component | *Frame, Trim covering* | ✓ |
| | Material Substitution | | |
| | i. Selection of recyclable materials | *Frame, Pad foam, Trim covering* | ✓ |
| | ii. Selection of reuse/remanufactured component | *Frame* | × |
| | iii. Selection of low impact materials (non-toxic, responsible sourced) | *Frame, Pad foam, Trim covering* | ✓ |
| | iv. Consider material longevity and durability (corrosion resistant, appropriate to use life) | *Frame, Pad foam, Trim covering* | × |
| | Material separation | | |
| | i. Avoid coating/lamination | *Frame, Trim covering* | ✓ |
| | ii. Limited use of adhesives | *Trim covering* | ✓ |
| **Energy** | Energy Minimisation | | |
| | Energy efficiency during use (efficient mechanism and operation of product) | *Seat* | - |
| | Energy source substitution | | |
| | Considering energy type and source during use (from safe and renewable sources) | *n/a* | - |
| **Water** | Water Minimisation | | |
| | Water efficiency during use (efficient mechanism and operation of product, reduce wastewater) | *n/a* | - |
| | Wastewater treatment | | |
| | Considering quality of discharge water after use | *n/a* | - |

## A4.5 Checklist for selecting resource efficient design strategy for production system design



Resource efficient strategy for production system design

| **Applicable SD approaches for production system** | **Please input 'Product/Component name' if a strategy is applicable** | **Improve PS candidate (✓) or not (×)** |
|---|---|---|
| **Material** | | |
| i. Near net shape | *Trim covering* | ✓ |
| ii. Waste in process minimisation | *Frame, Pad foam, Trim covering* | ✓ |
| iii. Selection of process which produce low/zero waste | *Frame, Pad foam, Trim covering* | ✓ |
| iv. Efficient packaging (minimised packaging materials and volume of packages) | *Frame, Pad foam, Trim covering, Seat* | × |
| v. Adoption of remanufacturing process | *Frame* | × |
| vi. Adoption of recycling process | *Frame, Pad foam, Trim covering* | ✓ |
| vii. Adoption of take back and collection methods | *Seat* | × |
| **Energy** | | |
| i. Minimise operation (Eliminate unnecessary operation) | *n/a* | - |
| ii. Selection of process which consume less energy (energy efficiency in production process) | *Pad foam* | ✓ |
| iii. Selection of energy type and source used in production (safe and renewable source) | *Frame, Pad foam, Trim covering* | ✓ |
| iv. Transportation method | *Frame, Pad foam, Trim covering, Seat* | × |
| v. Geographical location of manufacturing, operations and suppliers (Shortening Distance of transportation) | *Frame, Pad foam, Trim covering* | × |
| **Water** | | |
| i. Waste water minimisation | *n/a* | - |
| ii. Contaminated/Grey water minimisation | *n/a* | - |
| iii. Water recycling | *n/a* | - |

## A4.6 P&PS Design interrelation assessment (seat frame)

| Product: Seat Frame  | | Seat Frame Production | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 1. Source of material | 2. Type of fabricate machine (part production) | 3. Detail specification of fabricating machine (part production) | 4. Type of Assembly machine (part production) | 5. Detail specification of Assembly machine (part production) | 6. Source of production process/machine/tool | 7. Material flow (transportation from-to supplier and customer) | 8. Production and assembly flow (step of production) | 9. Production process standard and tolerance |
| Seat Frame | Material type | | 1 | 1 | | | 1 | | | |
| | Product Shape | | 1 | 1 | | | 1 | | | |
| | Product size | | 1 | 1 | | | 1 | | | |
| | Appearance of product | | 1 | 1 | | | 1 | | | |
| | Product durability | | 1 | 1 | | | 0 | | | |
| | The setting of tolerance and standard of product | | 1 | 1 | | | 1 | | | |
| | Product safety (e.g. Robustness) | | 1 | 1 | | | 0 | | | |
| | ergonomic factor | | 0 | 0 | | | 0 | | | |
| | environmental factor (e.g. Noise and vibration) | | 0 | 0 | | | 1 | | | |
| | maintenance factor | | 1 | 1 | | | 0 | | | |
| | key function of seat (e.g. foldable, lever,etc.) | | 1 | 1 | | | 1 | | | |
| | Additional function of seat (power seat, heater, etc.) | | 0 | 0 | | | 1 | | | |
| | Legislation | | 0 | 0 | | | 1 | | | |
| | Crash safety | | 0 | 0 | | | 0 | | | |
| | Productivity | | 1 | 1 | | | 1 | | | |
| | Homologation | | 0 | 0 | | | 0 | | | |

| Product: Seat Frame  | | Seat Frame Production | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 1. Source of material | 2. Type of fabricate machine (part production) | 3. Detail specification of fabricating machine (part production) | 4. Type of Assembly machine (part production) | 5. Detail specification of Assembly machine (part production) | 6. Source of production process/machine/tool | 7. Material flow (transportation from-to supplier and customer) | 8. Production and assembly flow (step of production) | 9. Production process standard and tolerance |
| Seat Frame | Material type | | | | | | | | | |
| | Product Shape | | | | | | | | | |
| | Product size | | | | | | | | | |
| | Appearance of product | | | | | | | | | |
| | Product durability | | | | | | | | | |
| | The setting of tolerance and standard of product | | | | | | | | | |
| | Product safety (e.g. Robustness) | | | | | | | | | |
| | ergonomic factor | | | | | | | | | |
| | environmental factor (e.g. Noise and vibration) | | | | | | | | | |
| | maintenance factor | | | | | | | | | |
| | key function of seat (e.g. foldable, lever,etc.) | | | | | | | | | |
| | Additional function of seat (power seat, heater, etc.) | | | | | | | | | |
| | Legislation | | | | | | | | | |
| | Crash safety | | | | | | | | | |
| | Productivity | | | | | | | | | |
| | Homologation | | | | | | | | | |

## A4.7 P&PS Design interrelation assessment (seat pad foam)

| Product: Seat Pad Foam | | Seat Pad Foam Production | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 1. Source of material | 2. Type of fabricate machine (part production) | 3. Detail specification of fabricating machine (part production) | 4. Type of Assembly machine (part production) | 5. Detail specification of Assembly machine (part production) | 6. Source of production process/machine/tool | 7. Material flow (transportation from-to supplier and customer) | 8. Production and assembly flow (step of production) | 9. Production process standard and tolerance |
| Seat Pad Foam | Material type | | 1 | 1 | | | 1 | | | |
| | Product Shape | | 1 | 1 | | | 1 | | | |
| | Product size | | 1 | 1 | | | 1 | | | |
| | Appearance of product | | 1 | 1 | | | 0 | | | |
| | Product durability | | 0 | 0 | | | 0 | | | |
| | The setting of tolerance and standard of product | | 1 | 1 | | | 1 | | | |
| | Product safety (e.g. Robustness) | | 1 | 1 | | | 0 | | | |
| | ergonomic factor | | 1 | 1 | | | 0 | | | |
| | environmental factor (e.g. Noise and vibration) | | 0 | 0 | | | 0 | | | |
| | maintenance factor | | 1 | 1 | | | 0 | | | |
| | key function of seat (e.g. foldable, lever,etc.) | | 0 | 0 | | | 0 | | | |
| | Additional function of seat (power seat, heater, etc.) | | 0 | 0 | | | 0 | | | |
| | Legislation | | 1 | 1 | | | 1 | | | |
| | Crash safety | | 0 | 0 | | | 0 | | | |
| | Productivity | | 1 | 1 | | | 1 | | | |
| | Homologation | | 0 | 0 | | | 0 | | | |

| Product: Seat Pad Foam | | Seat Pad Foam Production | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 1. Source of material | 2. Type of fabricate machine (part production) | 3. Detail specification of fabricating machine (part production) | 4. Type of Assembly machine (part production) | 5. Detail specification of Assembly machine (part production) | 6. Source of production process/machine/tool | 7. Material flow (transportation from-to supplier and customer) | 8. Production and assembly flow (step of production) | 9. Production process standard and tolerance |
| Seat Pad Foam | Material type | | | | | | | | | |
| | Product Shape | | | | | | | | | |
| | Product size | | | | | | | | | |
| | Appearance of product | | | | | | | | | |
| | Product durability | | | | | | | | | |
| | The setting of tolerance and standard of product | | | | | | | | | |
| | Product safety (e.g. Robustness) | | | | | | | | | |
| | ergonomic factor | | | | | | | | | |
| | environmental factor (e.g. Noise and vibration) | | | | | | | | | |
| | maintenance factor | | | | | | | | | |
| | key function of seat (e.g. foldable, lever,etc.) | | | | | | | | | |
| | Additional function of seat (power seat, heater, etc.) | | | | | | | | | |
| | Legislation | | | | | | | | | |
| | Crash safety | | | | | | | | | |
| | Productivity | | | | | | | | | |
| | Homologation | | | | | | | | | |

## A4.8 P&PS Design interrelation assessment (seat trim covering)

| Product: Seat Trim Covering | | Seat Trim Covering Production | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 1. Source of material | 2. Type of fabricate machine (part production) | 3. Detail specification of fabricating machine (part production) | 4. Type of Assembly machine (part production) | 5. Detail specification of Assembly machine (part production) | 6. Source of production process/machine/tool | 7. Material flow (transportation from-to supplier and customer) | 8. Production and assembly flow (step of production) | 9. Production process standard and tolerance |
| Seat Trim Covering | Material type | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | Product Shape | 0 | 0 | 1 | 0 | 1 | 0 | 0 | 0 | 1 |
| | Product size | 0 | 0 | 1 | 0 | 1 | 0 | 0 | 0 | 1 |
| | Appearance of product | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 1 |
| | Product durability | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 1 |
| | The setting of tolerance and standard of product | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 1 |
| | Product safety (e.g. Robustness) | 1 | 0 | 1 | 1 | 1 | 0 | 0 | 1 | 1 |
| | ergonomic factor | | | | | | | | | |
| | environmental factor (e.g. Noise and vibration) | 1 | 0 | 1 | 0 | 1 | 0 | 0 | 1 | 1 |
| | maintenance factor | 1 | 0 | 1 | 0 | 1 | 0 | 0 | 0 | 1 |
| | key function of seat (e.g. foldable, lever,etc.) | | | | | | | | | |
| | Additional function of seat (power seat, heater, etc.) | | | | | | | | | |
| | Legislation | 0 | 0 | 1 | 0 | 1 | 0 | 0 | 0 | 1 |
| | Crash safety | | | | | | | | | |
| | Productivity | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 |
| | Homologation | | | | | | | | | |

| Product: Seat Trim Covering | | Seat Trim Covering Production | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 1. Source of material | 2. Type of fabricate machine (part production) | 3. Detail specification of fabricating machine (part production) | 4. Type of Assembly machine (part production) | 5. Detail specification of Assembly machine (part production) | 6. Source of production process/machine/tool | 7. Material flow (transportation from-to supplier and customer) | 8. Production and assembly flow (step of production) | 9. Production process standard and tolerance |
| Seat Trim Covering | Material type | | 1 | 1 | 1 | | 1 | | | 1 |
| | Product Shape | | 0 | 1 | 0 | | 1 | | | 1 |
| | Product size | | 0 | 1 | 0 | | 1 | | | 1 |
| | Appearance of product | | 1 | 1 | 1 | | 0 | | | 1 |
| | Product durability | | 1 | 1 | 0 | | 0 | | | 1 |
| | The setting of tolerance and standard of product | | 1 | 1 | 1 | | 1 | | | 1 |
| | Product safety (e.g. Robustness) | | 0 | 1 | 0 | | 0 | | | 1 |
| | ergonomic factor | | 0 | 0 | 0 | | 0 | | | 0 |
| | environmental factor (e.g. Noise and vibration) | | 1 | 1 | 1 | | 0 | | | 1 |
| | maintenance factor | | 0 | 0 | 0 | | 0 | | | 1 |
| | key function of seat (e.g. foldable, lever,etc.) | | 0 | 0 | 0 | | 0 | | | 0 |
| | Additional function of seat (power seat, heater, etc.) | | 0 | 0 | 0 | | 0 | | | 0 |
| | Legislation | | 1 | 1 | 1 | | 1 | | | 1 |
| | Crash safety | | 0 | 0 | 0 | | 0 | | | 0 |
| | Productivity | | 1 | 1 | 1 | | 1 | | | 1 |
| | Homologation | | 0 | 0 | 0 | | 0 | | | 1 |

## A4.9 The original P&PS Design processes supporting creation of a single process

| Decision of Design Specification | | | stage | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Frame | Material type | 2 | ■ | | | X | | | | X | X | | | | | | | | | | | | | |
| 2 | Frame | Product Shape | 2 | X | ■ | X | | | | | X | X | | | | | | | | | | | | | |
| 3 | Frame | Product size | 2 | | X | ■ | | X | X | X | X | X | | | | | | | | | | | | | |
| 4 | Frame | Appearance of product | 2 | | | | ■ | | | | | X | | | | | | | | | | | | | |
| 5 | Frame | ergonomic factor | 2 | | | | | ■ | | | | | | | | | | | | | | | | | |
| 6 | Frame | key function of seat (e.g. foldable, lever,etc.) | 2 | | | | | X | ■ | | | | | | | | | | | | | | | | |
| 7 | Frame | Additional function of seat (power seat, heater, etc.) | 2 | | | | | X | | ■ | | | | | | | | | | | | | | | |
| 8 | Frame | Legislation | 2 | X | X | X | | | | | ■ | | | | | | | | | | | | | | |
| 9 | Frame | Product durability | all | X | X | | | | | | | ■ | | | | | | | | | | | | | |
| 10 | Pad foam | Product Shape | 2 | | X | | | | | | | | ■ | | | | X | | | | | | | | |
| 11 | Pad foam | Product size | 2 | | | X | | | | | | | | ■ | | | X | | | | | | | | |
| 12 | Pad foam | Appearance of product | 2 | | | | | X | | | | | | | ■ | X | X | | | | | | | | |
| 13 | Pad foam | ergonomic factor | 2 | | | | | X | | | | | | | | ■ | | | | | | | | | |
| 14 | Pad foam | Legislation | 2 | | | | | | | | | | | | | | ■ | | | | | | | | |
| 15 | Pad foam | Homologation | 2 | | | | | | | | | | X | X | | | X | ■ | | | | | | | |
| 16 | Pad foam | Product durability | all | | | | | | | | | | X | X | X | X | | | ■ | | | | | | |
| 17 | Trim coverin | Material type | 2 | | | | | | | | | | | | | | | | | ■ | | | X | X | |
| 18 | Trim coverin | Product Shape | 2 | | | | | | | | | | X | X | | | | | | X | ■ | | | X | |
| 19 | Trim coverin | Product size | 2 | | | | | | | | | | X | | | | | | | | X | ■ | | X | |
| 20 | Trim coverin | Appearance of product | 2 | | | | | | | | | | X | X | | | | | | X | X | X | ■ | | |
| 21 | Trim coverin | Legislation | 2 | | | | | | | | | | | | | | | | | X | | X | | ■ | |
| 22 | Trim coverin | Homologation | 2 | | | | | | | | | | | | | | | | | | | | | X | ■ |
| 23 | Trim coverin | Product durability | all | | | | | | | | | | | | | | | | | | | | | X | X |
| 24 | Frame | Crash safety | 3 | X | X | X | | | | | X | X | | | | | | | | | | | | | |
| 25 | Frame | Homologation | 3 | | | | | | | | | | | | | | | | | | | | | | |
| 26 | Pad foam | Material type | 3 | | | | | | | | | | | | X | | X | X | X | | | | | | |
| 27 | Pad foam | Crash safety | 3 | | | | | | | | | | | | | | X | | | | | | | | |
| 28 | Frame | The setting of tolerance and standard of product | 4 | X | X | X | X | | X | X | X | | | | | | | | | | | | | | |
| 29 | Frame | Product safety (e.g. Robustness) | 4 | X | | | | | | | X | | | | | | | | | | | | | | |
| 30 | Frame | environmental factor (e.g. Noise and vibration) | 4 | X | X | X | | | | | | | | | | | | | | | | | | | |
| 31 | Frame | maintenance factor | 4 | X | X | | | | X | X | | X | | | | | | | | | | | | | |
| 32 | Frame | Productivity | 4 | X | X | X | X | | | | | | | | | | | | | | | | | | |
| 33 | Pad foam | The setting of tolerance and standard of product | 4 | | | | | | | | | | X | X | X | | X | | | | | | | | |
| 34 | Pad foam | Product safety (e.g. Robustness) | 4 | | | | | | | | | | | | | | | | | | | | | | |
| 35 | Pad foam | environmental factor (e.g. Noise and vibration) | 4 | | | | | | | | | | X | X | X | | | | X | | | | | | |
| 36 | Pad foam | maintenance factor | 4 | | | | | | | | | | X | X | X | | X | | X | | | | | | |
| 37 | Pad foam | Productivity | 4 | | | | | | | | | | X | X | | | | | | | | | | | |
| 38 | Trim coverin | The setting of tolerance and standard of product | 4 | | | | | | | | | | | | | | | | | X | X | X | X | | |
| 39 | Trim coverin | Product safety | 4 | | | | | | | | | | | | | | | | | | | | | X | |
| 40 | Trim coverin | environmental factor (e.g. Noise and vibration, cleanliness) | 4 | | | | | | | | | | | | | | | | | X | | | X | | |
| 41 | Trim coverin | maintenance factor | 4 | | | | | | | | | | | | | | | | | X | | | | | |
| 42 | Trim coverin | Productivity | 4 | | | | | | | | | | | | | | | | | X | X | X | | | |
| 43 | Frame | Source of material | 6 | X | | | | | | | | | | | | | | | | | | | | | |
| 44 | Pad foam | Source of material | 6 | | | | | | | | | | | | | | | | | | | | | | |
| 45 | Pad foam | Source of production process/machine/tool | 6 | | | | | | | | | | X | X | | | | | | | | | | | |
| 46 | Trim coverin | Source of material | 6 | | | | | | | | | | | | | | | | | X | | | | | |
| 47 | Trim coverin | Source of production process/machine/tool | 6 | | | | | | | | | | | | | | | | | X | X | X | | | |
| 48 | Frame | Type of fabricate machine (part production) | 7 | X | X | X | | | | | X | | | | | | | | | | | | | | |
| 49 | Frame | Type of Assembly machine (part production) | 7 | X | X | X | | | | | X | | | | | | | | | | | | | | |
| 50 | Frame | Source of production process/machine/tool | 7 | X | X | X | | | | | | | | | | | | | | | | | | | |
| 51 | Frame | Production and assembly flow (step of production) | 7 | X | X | X | | | | | | | | | | | | | | | | | | | |
| 52 | Pad foam | Type of fabricate machine (part production) | 7 | | | | | | | | | | X | X | | | | | | | | | | | |
| 53 | Pad foam | Production and assembly flow (step of production) | 7 | | | | | | | | | | | | | | | | | | | | | | |
| 54 | Trim coverin | Type of fabricate machine (part production) | 7 | | | | | | | | | | | | | | | | | X | X | X | | | |
| 55 | Trim coverin | Type of Assembly machine (part production) | 7 | | | | | | | | | | | | | | | | | X | X | X | | | |
| 56 | Trim coverin | Production and assembly flow (step of production) | 7 | | | | | | | | | | | | | | | | | | | | | | |
| 57 | Frame | Detail specification of fabricating machine (part production) | 8 | X | X | X | | | | | | | | | | | | | | | | | | | |
| 58 | Frame | Detail specification of Assembly machine (part production) | 8 | X | X | X | | | | | | | | | | | | | | | | | | | |
| 59 | Frame | Material flow (transportation from-to supplier and customer) | 8 | | | | | | | | | | | | | | | | | | | | | | |
| 60 | Frame | Production process standard and tolerance | 8 | X | X | X | | | | | | | | | | | | | | | | | | | |
| 61 | Pad foam | Detail specification of fabricating machine (part production) | 8 | | | | | | | | | | X | X | X | | X | | X | | | | | | |
| 62 | Pad foam | Material flow (transportation from-to supplier and customer) | 8 | | | | | | | | | | | | | | | | | | | | | | |
| 63 | Pad foam | Production process standard and tolerance | 8 | | | | | | | | | | | | | | | | | | | | | | |
| 64 | Trim coverin | Detail specification of fabricating machine (part production) | 8 | | | | | | | | | | | | | | | | | X | X | X | X | | |
| 65 | Trim coverin | Detail specification of Assembly machine (part production) | 8 | | | | | | | | | | | | | | | | | X | X | X | X | | |
| 66 | Trim coverin | Material flow (transportation from-to supplier and customer) | 8 | | | | | | | | | | | | | | | | | | | | | | |
| 67 | Trim coverin | Production process standard and tolerance | 8 | | | | | | | | | | | | | | | | | X | X | X | X | | |

## A4.9 The original P&PS Design processes supporting creation of a single process (continue)

| Decision of Design Specification | | | stage | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 | 32 | 33 | 34 | 35 | 36 | 37 | 38 | 39 | 40 | 41 | 42 | 43 | 44 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Frame | Material type | 2 | | X | X | | | | X | X | | X | | | | | | | | | | | | |
| 2 | Frame | Product Shape | 2 | | X | X | | | | X | X | | X | | | | | | | | | | | | |
| 3 | Frame | Product size | 2 | | X | X | | | | X | X | | X | | | | | | | | | | | | |
| 4 | Frame | Appearance of product | 2 | | | | | | | | | | | | | | | | | | | | | | |
| 5 | Frame | ergonomic factor | 2 | | | | | | | | | | | | | | | | | | | | | | |
| 6 | Frame | key function of seat (e.g. foldable, lever,etc.) | 2 | | | | | | | | | | | | | | | | | | | | | | |
| 7 | Frame | Additional function of seat (power seat, heater, etc.) | 2 | | | | | | | | | | | | | | | | | | | | | | |
| 8 | Frame | Legislation | 2 | | | | | | | | | | | | | | | | | | | | | | |
| 9 | Frame | Product durability | all | | | | | | | | | | | | | | | | | | | | | | |
| 10 | Pad foam | Product Shape | 2 | | | | | | | | | | | | | | | | | | | | | | |
| 11 | Pad foam | Product size | 2 | | | | | | | | | | | | | | | | | | | | | | |
| 12 | Pad foam | Appearance of product | 2 | | | | | | | | | | | | | | | | | | | | | | |
| 13 | Pad foam | ergonomic factor | 2 | | | | | | | | | | | | | | | | | | | | | | |
| 14 | Pad foam | Legislation | 2 | | | | | | | | | | | | | | | | | | | | | | |
| 15 | Pad foam | Homologation | 2 | | | | | | | | | | | | | | | | | | | | | | |
| 16 | Pad foam | Product durability | all | | | | | | | | | | | | | | | | | | | | | | |
| 17 | Trim coverin | Material type | 2 | | | | | | | | | | | | | | | | | | | | | | |
| 18 | Trim coverin | Product Shape | 2 | | | | | | | | | | | | | | | | | | | | | | |
| 19 | Trim coverin | Product size | 2 | | | | | | | | | | | | | | | | | | | | | | |
| 20 | Trim coverin | Appearance of product | 2 | | | | | | | | | | | | | | | | | | | | | | |
| 21 | Trim coverin | Legislation | 2 | X | X | | | | | | | | | | | | | | | | | | | | |
| 22 | Trim coverin | Homologation | 2 | X | | | | | | | | | | | | | | | | | | | | | |
| 23 | Trim coverin | Product durability | all | ■ | | | | | | | | | | | | | | | | | | | | | |
| 24 | Frame | Crash safety | 3 | | ■ | X | | | | | | | | | | | | | | | | | | | |
| 25 | Frame | Homologation | 3 | | | ■ | | | | | | | | | | | | | | | | | | | |
| 26 | Pad foam | Material type | 3 | | | | ■ | | | | | | | | | | | | | | | | | | |
| 27 | Pad foam | Crash safety | 3 | | | | | ■ | | | | | | | | | | | | | | | | | |
| 28 | Frame | The setting of tolerance and standard of product | 4 | | | | | | ■ | | | X | X | | | | | | | | | | | | |
| 29 | Frame | Product safety (e.g. Robustness) | 4 | | X | X | | | X | ■ | X | X | | | | | | | | | | | | | |
| 30 | Frame | environmental factor (e.g. Noise and vibration) | 4 | | | | | | X | | ■ | | | | | | | | | | | | | | |
| 31 | Frame | maintenance factor | 4 | | | | | | | | | ■ | | | | | | | | | | | | | |
| 32 | Frame | Productivity | 4 | | | | | | | | | | ■ | | | | | | | | | | | | |
| 33 | Pad foam | The setting of tolerance and standard of product | 4 | | | | X | | | | | | | ■ | | | | X | | | | | | | |
| 34 | Pad foam | Product safety (e.g. Robustness) | 4 | | | | | X | | | | | | | ■ | | | | | | | | | | |
| 35 | Pad foam | environmental factor (e.g. Noise and vibration) | 4 | | | | X | | | | | | | | | ■ | | | | | | | | | |
| 36 | Pad foam | maintenance factor | 4 | | | | X | | | | | | | | X | X | ■ | | | | | | | | |
| 37 | Pad foam | Productivity | 4 | | | | X | | | | | | | | | | | ■ | | | | | | | |
| 38 | Trim coverin | The setting of tolerance and standard of product | 4 | | | | | | | | | | | | | | | | ■ | | | | | | |
| 39 | Trim coverin | Product safety | 4 | | | | | | | | | | | | | | | | | ■ | | | | | |
| 40 | Trim coverin | environmental factor (e.g. Noise and vibration, cleanliness) | 4 | X | | | | | | | | | | | | | | | | | ■ | | | | |
| 41 | Trim coverin | maintenance factor | 4 | | | | | | | | | | | | | | | | | | | ■ | | | |
| 42 | Trim coverin | Productivity | 4 | | | | | | | | | | | | | | | | | | | | ■ | | |
| 43 | Frame | Source of material | 6 | | | | | | | | | | X | | | | | | | | | | | ■ | |
| 44 | Pad foam | Source of material | 6 | | | | X | | | | | | | | | | | X | | | | | | | ■ |
| 45 | Pad foam | Source of production process/machine/tool | 6 | | | | X | | | | | | | | | | | X | | | | | | | |
| 46 | Trim coverin | Source of material | 6 | | | | | | | | | | | | | | | | | | | | | | |
| 47 | Trim coverin | Source of production process/machine/tool | 6 | | | | | | | | | | | | | | | | | | | | X | | |
| 48 | Frame | Type of fabricate machine (part production) | 7 | | | | | | | | | | X | | | | | | | | | | | | |
| 49 | Frame | Type of Assembly machine (part production) | 7 | | | | | | | | | | X | | | | | | | | | | | | |
| 50 | Frame | Source of production process/machine/tool | 7 | | | | | | | | | | X | | | | | | | | | | | | |
| 51 | Frame | Production and assembly flow (step of production) | 7 | | | | | | | | | | X | | | | | | | | | | | X | |
| 52 | Pad foam | Type of fabricate machine (part production) | 7 | | | | | | | | | | | | | | | X | | | | | | | |
| 53 | Pad foam | Production and assembly flow (step of production) | 7 | | | | | | | | | | | | | | | | | | | | | X | X |
| 54 | Trim coverin | Type of fabricate machine (part production) | 7 | | | | | | | | | | | | | | | | X | | | | X | | |
| 55 | Trim coverin | Type of Assembly machine (part production) | 7 | | | | | | | | | | | | | | | | X | | | | X | | |
| 56 | Trim coverin | Production and assembly flow (step of production) | 7 | | | | | | | | | | | | | | | | | | | | X | X | X |
| 57 | Frame | Detail specification of fabricating machine (part production) | 8 | | X | | | | | X | X | X | | | | | | | | | | | | | |
| 58 | Frame | Detail specification of Assembly machine (part production) | 8 | | X | | | | | X | X | X | | | | | | | | | | | | | |
| 59 | Frame | Material flow (transportation from-to supplier and customer) | 8 | | | | | | | | | | | | | | | | | | | | | X | |
| 60 | Frame | Production process standard and tolerance | 8 | | | | | | | | | | | | | | | | | | | | | | |
| 61 | Pad foam | Detail specification of fabricating machine (part production) | 8 | | | | | | | | | | | | | | | | | | | | | | |
| 62 | Pad foam | Material flow (transportation from-to supplier and customer) | 8 | | | | | | | | | | | | | | | | | | | | | X | X |
| 63 | Pad foam | Production process standard and tolerance | 8 | | | | | | | | | | | X | | X | X | X | | | | | | | |
| 64 | Trim coverin | Detail specification of fabricating machine (part production) | 8 | | | | | | | | | | | | | | | | | | | | | | |
| 65 | Trim coverin | Detail specification of Assembly machine (part production) | 8 | | | | | | | | | | | | | | | | | | | | | | |
| 66 | Trim coverin | Material flow (transportation from-to supplier and customer) | 8 | | | | | | | | | | | | | | | | | | | | | X | X |
| 67 | Trim coverin | Production process standard and tolerance | 8 | | | | | | | | | | | | | | | | | | | | | | |

## A4.9 The original P&PS Design processes supporting creation of a single process (continue)

| Decision of Design Specification | | | stage | 45 | 46 | 47 | 48 | 49 | 50 | 51 | 52 | 53 | 54 | 55 | 56 | 57 | 58 | 59 | 60 | 61 | 62 | 63 | 64 | 65 | 66 | 67 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Frame | Material type | 2 | | | | 2 | | 2 | | | | | | | 2 | | | | | | | | | | |
| 2 | Frame | Product Shape | 2 | | | | 2 | | 2 | | | | | | | 2 | | | | | | | | | | |
| 3 | Frame | Product size | 2 | | | | 2 | | 2 | | | | | | | 2 | | | | | | | | | | |
| 4 | Frame | Appearance of product | 2 | | | | 2 | | 2 | | | | | | | 2 | | | | | | | | | | |
| 5 | Frame | ergonomic factor | 2 | | | | | | | | | | | | | | | | | | | | | | | |
| 6 | Frame | key function of seat (e.g. foldable, lever,etc.) | 2 | | | | 2 | | 2 | | | | | | | 2 | | | | | | | | | | |
| 7 | Frame | Additional function of seat (power seat, heater, etc.) | 2 | | | | | | 2 | | | | | | | | | | | | | | | | | |
| 8 | Frame | Legislation | 2 | | | | | | 2 | | | | | | | | | | | | | | | | | |
| 9 | Frame | Product durability | all | | | | 2 | | | | | | | | | 2 | | | | | | | | | | |
| 10 | Pad foam | Product Shape | 2 | 2 | | | | | | | 2 | | | | | | | | | 2 | | | | | | |
| 11 | Pad foam | Product size | 2 | 2 | | | | | | | 2 | | | | | | | | | 2 | | | | | | |
| 12 | Pad foam | Appearance of product | 2 | | | | | | | | 2 | | | | | | | | | 2 | | | | | | |
| 13 | Pad foam | ergonomic factor | 2 | | | | | | | | 2 | | | | | | | | | 2 | | | | | | |
| 14 | Pad foam | Legislation | 2 | 2 | | | | | | | 2 | | | | | | | | | 2 | | | | | | |
| 15 | Pad foam | Homologation | 2 | | | | | | | | | | | | | | | | | | | | | | | |
| 16 | Pad foam | Product durability | all | | | | | | | | | | | | | | | | | | | | | | | |
| 17 | Trim coverin | Material type | 2 | | 2 | 2 | | | | | | | 2 | 2 | 2 | | | | | | | | 2 | 2 | 2 | 2 |
| 18 | Trim coverin | Product Shape | 2 | | | 2 | | | | | | | | | | | | | | | | | 2 | 2 | | 2 |
| 19 | Trim coverin | Product size | 2 | | | 2 | | | | | | | | | | | | | | | | | 2 | 2 | | 2 |
| 20 | Trim coverin | Appearance of product | 2 | | 2 | 2 | | | | | | | 2 | 2 | | | | | | | | | 2 | 2 | | 2 |
| 21 | Trim coverin | Legislation | 2 | | | 2 | | | | | | | 2 | 2 | | | | | | | | | 2 | 2 | | 2 |
| 22 | Trim coverin | Homologation | 2 | | | | | | | | | | | | | | | | | | | | | | | 2 |
| 23 | Trim coverin | Product durability | all | | 2 | | | | | | | | 2 | 2 | | | | | | | | | 2 | 2 | | 2 |
| 24 | Frame | Crash safety | 3 | | | | | | | | | | | | | | | | | | | | | | | |
| 25 | Frame | Homologation | 3 | | | | | | | | | | | | | | | | | | | | | | | |
| 26 | Pad foam | Material type | 3 | 2 | | | | | | | 2 | | | | | | | | | 2 | | | | | | |
| 27 | Pad foam | Crash safety | 3 | | | | | | | | | | | | | | | | | | | | | | | |
| 28 | Frame | The setting of tolerance and standard of product | 4 | | | | 2 | | 2 | | | | | | | 2 | | | | | | | | | | |
| 29 | Frame | Product safety (e.g. Robustness) | 4 | | | | 2 | | | | | | | | | 2 | | | | | | | | | | |
| 30 | Frame | environmental factor (e.g. Noise and vibration) | 4 | | | | | | 2 | | | | | | | | | | | | | | | | | |
| 31 | Frame | maintenance factor | 4 | | | | 2 | | | | | | | | | 2 | | | | | | | | | | |
| 32 | Frame | Productivity | 4 | | | | 2 | | 2 | | | | | | | 2 | | | | | | | | | | |
| 33 | Pad foam | The setting of tolerance and standard of product | 4 | 2 | | | | | | | 2 | | | | | | | | | 2 | | | | | | |
| 34 | Pad foam | Product safety (e.g. Robustness) | 4 | | | | | | | | 2 | | | | | | | | | 2 | | | | | | |
| 35 | Pad foam | environmental factor (e.g. Noise and vibration) | 4 | | | | | | | | | | | | | | | | | | | | | | | |
| 36 | Pad foam | maintenance factor | 4 | | | | | | | | 2 | | | | | | | | | 2 | | | | | | |
| 37 | Pad foam | Productivity | 4 | 2 | | | | | | | 2 | | | | | | | | | 2 | | | | | | |
| 38 | Trim coverin | The setting of tolerance and standard of product | 4 | | | 2 | | | | | | | 2 | 2 | | | | | | | | | 2 | 2 | | 2 |
| 39 | Trim coverin | Product safety | 4 | | 2 | | | | | | | | | 2 | | | | | | | | | 2 | 2 | | 2 |
| 40 | Trim coverin | environmental factor (e.g. Noise and vibration, cleanliness) | 4 | | 2 | | | | | | | | 2 | 2 | 2 | | | | | | | | 2 | 2 | | 2 |
| 41 | Trim coverin | maintenance factor | 4 | | 2 | | | | | | | | | | | | | | | | | | 2 | 2 | | 2 |
| 42 | Trim coverin | Productivity | 4 | | | 2 | | | | | | | 2 | 2 | 2 | | | | | | | | 2 | 2 | 2 | 2 |
| 43 | Frame | Source of material | 6 | | | | | | | | | | | | | | | | | | | | | | | |
| 44 | Pad foam | Source of material | 6 | | | | | | | | | | | | | | | | | | | | | | | |
| 45 | Pad foam | Source of production process/machine/tool | 6 | ■ | | | | | | | | | | | | | | | | | | | | | | |
| 46 | Trim coverin | Source of material | 6 | | ■ | | | | | | | | | | | | | | | | | | | | | |
| 47 | Trim coverin | Source of production process/machine/tool | 6 | | | ■ | | | | | | | | | | | | | | | | | | | | |
| 48 | Frame | Type of fabricate machine (part production) | 7 | | | | ■ | | | | | | | | | | | | | | | | | | | |
| 49 | Frame | Type of Assembly machine (part production) | 7 | | | | | ■ | | | | | | | | | | | | | | | | | | |
| 50 | Frame | Source of production process/machine/tool | 7 | | | | x | x | ■ | | | | | | | | | | | | | | | | | |
| 51 | Frame | Production and assembly flow (step of production) | 7 | | | | | x | x | ■ | | | | | | | | | | | | | | | | |
| 52 | Pad foam | Type of fabricate machine (part production) | 7 | | | | | | | | ■ | | | | | | | | | | | | | | | |
| 53 | Pad foam | Production and assembly flow (step of production) | 7 | x | | | | | x | x | x | ■ | | | | | | | | | | | | | | |
| 54 | Trim coverin | Type of fabricate machine (part production) | 7 | | | | | | | | | | ■ | | | | | | | | | | | | | |
| 55 | Trim coverin | Type of Assembly machine (part production) | 7 | | | | | | | | | | | ■ | | | | | | | | | | | | |
| 56 | Trim coverin | Production and assembly flow (step of production) | 7 | x | x | x | | | | | | | x | x | ■ | | | | | | x | | | | x | |
| 57 | Frame | Detail specification of fabricating machine (part production) | 8 | | | | x | x | x | | | | | | | ■ | | | | | | | | | | |
| 58 | Frame | Detail specification of Assembly machine (part production) | 8 | | | | x | x | x | | | | | | | | ■ | | | | | | | | | |
| 59 | Frame | Material flow (transportation from-to supplier and customer) | 8 | | | | | | x | | | | | | | | | ■ | | | | | | | | |
| 60 | Frame | Production process standard and tolerance | 8 | | | | x | x | | | | | | | | x | x | | ■ | | | | | | | |
| 61 | Pad foam | Detail specification of fabricating machine (part production) | 8 | | | | | | | | | | | | | | | | | ■ | | | | | | |
| 62 | Pad foam | Material flow (transportation from-to supplier and customer) | 8 | x | | | | | x | | | | | | | | | | | | ■ | | | | | |
| 63 | Pad foam | Production process standard and tolerance | 8 | | | | | | | | x | | | | | | | | | x | | ■ | | | | |
| 64 | Trim coverin | Detail specification of fabricating machine (part production) | 8 | | x | x | | | | | | | x | | | | | | | | | | ■ | | | |
| 65 | Trim coverin | Detail specification of Assembly machine (part production) | 8 | | x | x | | | | | | | | x | | | | | | | | | | ■ | | |
| 66 | Trim coverin | Material flow (transportation from-to supplier and customer) | 8 | x | x | x | | | x | | | | x | x | | | | | | | | | | | ■ | |
| 67 | Trim coverin | Production process standard and tolerance | 8 | | | | | | | | | | x | x | | | | | | | | | | | | ■ |

# APPENDIX V THE SUSTAINABLE CO-DESIGN OF PRODUCTS AND PRODUCTION SYSTEMS

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15th Global Conference on Sustainable Manufacturing

# The Sustainable Co-Design of Products and Production Systems

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**Abstract**

The challenges in designing products and production systems are becoming increasingly complex due to more changeable customer demands, frequent product updates, and the requirements for resource efficiency. Established design processes are often unable to readily accommodate these rapid changes. In addition, incremental benefits are often achieved through existing sustainable design approaches due to inability to fully assess the impacts of product design improvements and their associated implications within production facilities. This highlights the need for more integrated design processes that enable seamless co-development of products and production systems. This paper examines the current interrelation and interaction of these design processes from the resource efficiency viewpoint, proposes a novel sustainable 'Co-Design' model, and discusses the ecological benefits of co-designing future products and production systems.

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*Keywords:* Integrated co-design processes; Sustainable design; Resource-Efficient Manufacturing.

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## 1. Introduction

Customisation, changing demand, shorter product life and frequent product updates, as well as the requirements for improving resource efficiency all necessitate a closer integration of design processes for products and their associated production systems [1,2]. At present, this is usually accomplished through integrating concepts such as 'concurrent engineering' which are often supported by information sharing technologies [3]. Nevertheless, these

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approaches have often been reported as insufficient for responding to the dynamic requirements of contemporary product development processes [4], which highlight a need for novel approach where a single methodology is used for both design processes [1]. This paper proposes a 'co-design model' to support a closer integration design processes used for Products and Production System (P&PS), as depicted in Fig.1. With this aim, the literature related to integrated design concepts is reviewed, the interrelation and interaction of existing integrated design are analysed, and a co-design methodology for P&PS is presented.

## 2. The State-of-Art in Integrated Design of Product and Production Systems

Production system design is normally driven by the specific requirements of an existing and/or predesigned product. This is referred to as the 'throw over the wall' concept, which often causes long lead time, increased development costs, low product quality, and a frequent need for redesign of products and/or production systems [5]. To mitigate these difficulties, concurrent engineering was proposed with the aim *"of having integrated, concurrent design of products and their related processes, including manufacture and support."* [6]. From the literature, several key characteristics that leads to the success of integrated design can be identified (See Fig.2). These includes: encouraging parallel activities, considering critical issues early in design, exchanging information, and maintaining collaboration between teams. To address these core characteristics, following four corresponding research themes have emerged in relevant publications:

Firstly, the **'Integrated design process'** such as Integrated Product Development (IPD) and the development process of Ulrich and Eppinger are generally represented in a context of an integration of parallel activities from different processes e.g. marketing, product design, and production development. These generally suggested how an integrated design can be managed through step-by-step activities performed by different stakeholders and present the information flow during integrated design. However, these processes are not widely adopted in industries because they typically provide simple instructions and could not deal with practical complexities [3].

For **'Specific improvement of design process performance'** theme, the proposed methods commonly utilise one or two integrated design characteristics for enhancing the specific performances of a product, a production system and/or a development process without a guidance for collaboration among design teams. For example, the Design for Manufacture (DfM) has been proposed to improve manufacturability of products by embedding manufacturing information and knowledge into product design process [7]. Likewise, traditional Quality Function Deployment (QFD) has been applied to present product and production system specification to negotiate design and production preference by product designers instead of collaborative consideration from both parties [8].

Thirdly, **'Technological tools to support integration'** are introduced for sharing design information. Examples of these analytical software packages are DFMA and SEER DFM which offer faster manufacturability using essential information [5]. Moreover, the information and knowledge management tools have traditionally been used via computer aid design and manufacture (CAD-CAM) by product designers to obtain relevant knowledge and data on production processes [8,9]. The STandard for the Exchange of Product (STEP) data has been developed for standardising and facilitating product-related data exchange among different information and knowledge based systems in a product life cycle. It has been highlighted that most of the developments in this area were regarded the

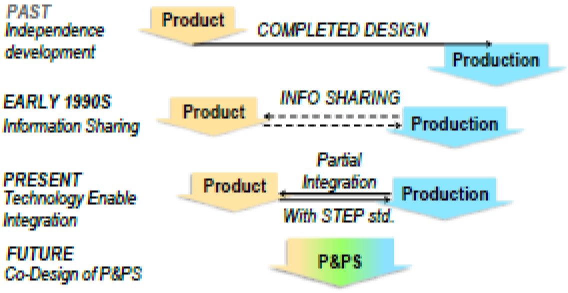


Fig. 1. The proposed evolution of sustainable co-design

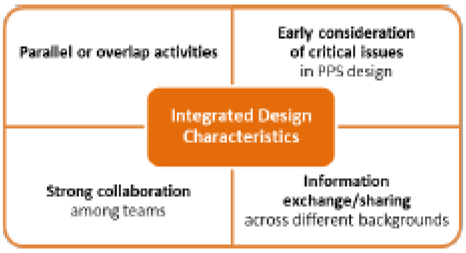


Fig. 2. Four main characteristics of the integrated design concepts

product; therefore, there is a need for progressing standard and information model related production system [10].

Finally, a '**Strong Collaboration**' theme for integrated design has been introduced to discover the fundamental success factors and risk of collaboration in product development and to identify how these can be managed and enhanced. Büyüközkan & Arsenyan [11] concluded that the essential success factors of collaboration are communication and trust. Further studies focused on various aspects of communication e.g. influential collaboration factors, information exchange and cognitive behavior in team communication during development phase [8,12].

In practice, several integrated design processes have been implemented for cost reduction and improved responsiveness by various large manufacturing companies such as Hewlett-Packard and General Motors [5]. Nevertheless, many of these efforts have not obtained perceptible benefits from integrated design because of the lack of a structured collaborative approach, inaccessibility of information and knowledge, and practical planning complexities within development process [8]. A common observation in most of these applications is that integrated design concepts should not mainly utilised to meet a narrow target such as cost and time reduction, and must explore wider potential benefits such as improved resource efficiency [1,2]. Besides, these integrated design concepts are typically unidirectional approaches mainly assisting the product designers to consider manufacturability [4]. This highlights that the design of production systems is often 'an outcome of decided product design', which may limit the potential benefits of a truly integrated and simultaneous approach to design of P&PS.

## 3. The Interrelation and Interaction Requirement in Integrated Design

The traditional integrated design concepts aim to transform sequential tasks into overlapped tasks to reduce design and development lead time. In general, identification and specification of overlapping tasks often depends on a task interrelation and interaction as described below.

### *3.1. The Interrelation Challenges between Design Processes*

An interrelation (or interdependency) is the term used to identify the relationship between two design tasks or activities subject to the required information in task execution. The relationship between two tasks can be classified as [13]:

*a) Independent relationship* when two tasks require no information from one another to execute their operation. To apply integrated design, these tasks can be freely undertaken in a completely overlapped/parallel pattern.

*b) Dependent relationship* when a task requires information/data from a preceding task. Hence, these two tasks are processed in a sequential pattern. To apply integrated design, this pair of dependent tasks can be partially overlapped through early sharing of preliminary information.

*c) Interdependent relationship* when two tasks require information exchange from each other and any changes to one task directly cause reconsideration (rework) of another. These interdependent tasks can be arranged to partially overlap at the beginning, and then, information and decisions made by each task are unidirectionally transferred backward-and-forward until final decisions are agreed.

Due to the considerable focus on reduction of development time, the completely overlapped/parallel pattern of tasks with the independent relationship is often desirable. In addition, the integration of dependent tasks is less complicated than interdependent tasks. Therefore, several studies offered methods to mitigate the complexity via the separation of interdependent tasks. For example, a well-known approach refers to as Design Structure Matrix (DSM) which was originally proposed for relationship identification, is frequently being adapted to manage the interdependent tasks [13]. As part of the existing sequential design processes for P&PS (see Fig.3), most of the production development tasks such as system concept, system configuration, and detail system development require information from completed tasks (e.g. conceptual product design, product assembly scheme, and complete product documentation) from product design. The current integrated design predominately focuses on timely development instead of identifying, prioritising, and managing design tasks based on their significance to mitigate unexpected concerns and redesign. Moreover, these design tasks are principally formed by advancing the execution of product development (unidirectional information transfer), and as the result, the critical decisions requiring collaborative considerations from various areas of expertise are often overlooked, limiting the significant potential that could be offered through a concurrent approach to co-design of P&PS.

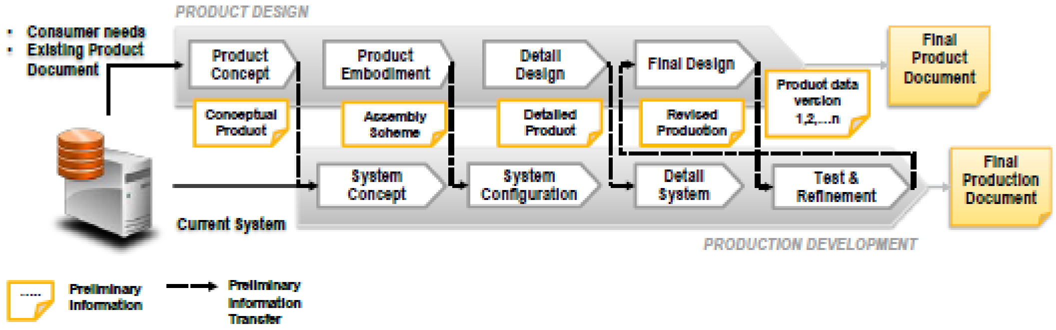


Fig. 3. The relationship of design processes of products and production systems

To advance the integration of P&PS design, the critical decisions which can initiate any failures, redesign issues or ecological concern, should be carefully deliberated with sufficient knowledge and information from related design teams to unlock the potential solution. Tools and methods exist to address each of these challenges in isolation, for example Failure Modes and Effects Analysis and Life Cycle Assessment [2,5], however they are often used in isolation and not with a visibility across both product and production system design. Therefore, the critical decisions should be specified and evolved in such a way as to foster an interdependent relationship between design tasks based on a 'bi-directional' flow of information and knowledge. This enables a wider range of potential benefits, including consideration of resource efficiency to be investigated across various design tasks and more importantly from the outset of the integrated P&PS design process.

### *3.2. The Interaction Challenges between Design Processes*

To create integrated tasks, the interaction between two design teams should be structurally managed. The different level of human interactions can be simply described based on three different levels [8], namely:

*a) Coordination* – 'unidirectional' managing of tasks done by different teams or different hierarchies (such as management and staff) with different objectives.

*b) Cooperation* – 'bi-directional' management of tasks performed by individuals or teams who share resources, procedures, and benefits.

*c) Collaboration* – is used when the task is unachievable by an individual because of knowledge complexity and resource limitations. Lu *et al.* [8] defines collaboration as *"teams of individuals to work on tasks that not only have shared resources (coordination) and shared outcomes (cooperation), but most essentially, shared a common goal"*.

In majority of applications, the more advanced level of interaction (i.e. collaboration) is most likely only achievable if the preliminary interaction levels (i.e. coordination and cooperation) have already been established. The methods and tools in the existing design interactions, such as Quality Function Deployment, and CAD-CAM tools [8], often appear to be limited in scope and only promote the 'unidirectional coordination' via task overlapping and information sharing [14]. Due to complexities in design tasks, the interactions for closely integrated design should be formed at cooperation or collaboration level using the effective implementation of communication and collaboration management. This highlights a clear need to explore the detail nature of required interactions within co-design of P&PS to achieve targeted ecological benefits.

## 4. Co-Design of Products and Production Systems to Support Sustainability Challenges

Current integrated design is frequently applied to shorten development time through the early development of production system. This practice still cannot truly prevent a possible failure and redesign issue due to the lack of knowledge and inability to effectively evaluate the impact of product design decisions on production systems requirements. Worryingly, this 'fix it later' approach also appears to be present in sustainable design and manufacturing applications, in which the potential benefits are limited by the late considerations of sustainability issues within the design process and/or inability to fully assess the direct and indirect impacts of product design improvements within production facilities. Manufacturers are often unwilling to replace the existing production processes with the ones that produced lower ecological footprints and required less resource consumption if significant additional investment is required. Hence, designers should clearly understand the relations between products and production systems and be able to identify, assess, and select all the most ecological options.

With this aim, a **'Co-Design'** model has been proposed as a combined design which enables seamless and concurrent co-development of P&PS. In addition to ecological benefits, in particular related to resource efficiency, such a co-design approach is expected to provide other benefits including reduction of cost and development time, improved quality and manufacturability of products, and the opportunity for mass customisation and personalisation of product designs, as shown in Fig.4. Within this approach, the vital design decisions related to ecological improvements, will be identified and addressed through a simultaneous collaboration between designers of P&PS. The improved collaboration provides the ability to gain an insight into the impact of various possible design improvements and enables a what-if scenario planning to maximise the potential for resource efficiency. For instance, through the exchange of knowledge, P&PS designers can collaboratively choose from wider options such as materials substitution for improved recyclability, new more energy-efficient technologies, or low impact none-chemical processes within the production system. In addition, the flexibility offered through co-design not only facilitates the requirement for frequent changes imposed by market conditions, but also removes obstacles in minimising the overall environmental impact during a product lifecycle.

## 5. The Sustainable Co-Design of Products and Production Systems

The proposed approach for sustainable co-design of P&PS is depicted in Fig.5. The main objective of this approach is to elevate the significance of design decisions related to ecological issues and improve this decision making by providing timely insight into the ecological interrelations (eco-interrelation) and interactions among these design processes. Typically, the adoption of such co-design for P&PS involves an evolutionary process to transform existing independent design procedures through identifying eco-interrelations and interactions that need to be established. This is achieved by decomposition of various tasks within product and production system design, each of which contain several significant decisions, and systematically pairing them up using a mapping process based on their interrelations and interactions. Clearly, such decomposition, rearranging, and re-sequencing of design tasks will greatly depend on the specific requirements, complexities, and structures of a particular application. For example, when the design tasks are carried out by a design team within a small OEM (i.e. simple central design process), the definition and implementation of eco-interrelations and interactions are much more manageable than cases where due to product and/or production complexities, many design teams across various actors within a supply chain are involved in design tasks (complex distributed design process) [1].

The sustainable co-design of P&PS can be achieved when the interdependent relationships are defined and performed through the following steps.

**I: Feasibility of Co-Design Adoption**

The starting task within the Co-Design model aims to identify the necessity to design P&PS with a single design process and to highlight potential benefit. In the first step, a Co-Design manger is assigned to collect information, define Co-Design processes and develop and monitor cooperation and collaboration P&PS design teams. Then, the existing design processes are evaluated and classified through determination of their three fundamental characteristics, namely the frequency of design update, the relationship between product design and production system design updates, and the potential impact for improving resource efficiency.

**II: Assessment of Design Processes**

The purpose of the second step is to specify the ecological interdependencies between P&PS design specification to identify where collaborative considerations are required to significantly improve resource efficiency. Firstly, the product complexity and design organisation structure need to be studied, since these two aspects will greatly influence the integration of design processes. Then, design processes are analysed to classify and assign the critical decisions at product design specification (PDS) and production system design specification (PSDS) level. Finally, the ecological interrelations between PDSs and PSDSs are examined and defined.

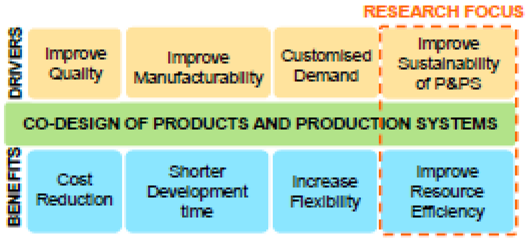


Fig. 4. Drivers and benefits of co-design of P&PS

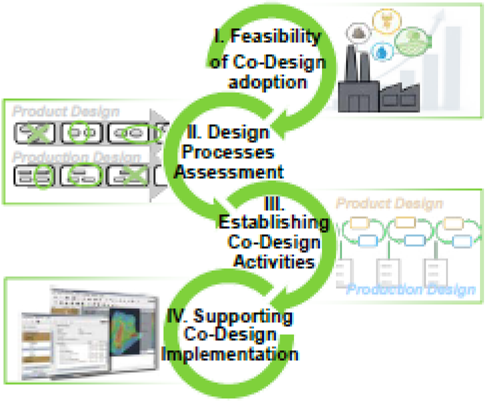


Fig. 5. The Sustainable Co-Design of Products and Production Systems

### III: Establishing Co-Design Processes

Based on the results of the assessment in the second step, it may not be necessary for every manufacturing company to change its entire existing design processes into a single co-design approach. Therefore, in this step three gradual and progressive optional methods are considered to assist various manufacturing companies to create co-design. Firstly, in cases where only a few critical decisions should 'co-considered', the co-design can simply be achieved by adding targeted cooperation into the current design processes. Secondly, in cases where there are critical decisions among a subset of design stages (e.g. product and system concept development), these should be managed through targeted P&PS collaboration at relevant product design stage. Finally, in the case where there are several complex and critical decisions across various design stages, co-design should be managed through a single combined design process developed based on Design Structure Matrix [15]. This new co-design process will often necessitate reskilling P&PS designers.

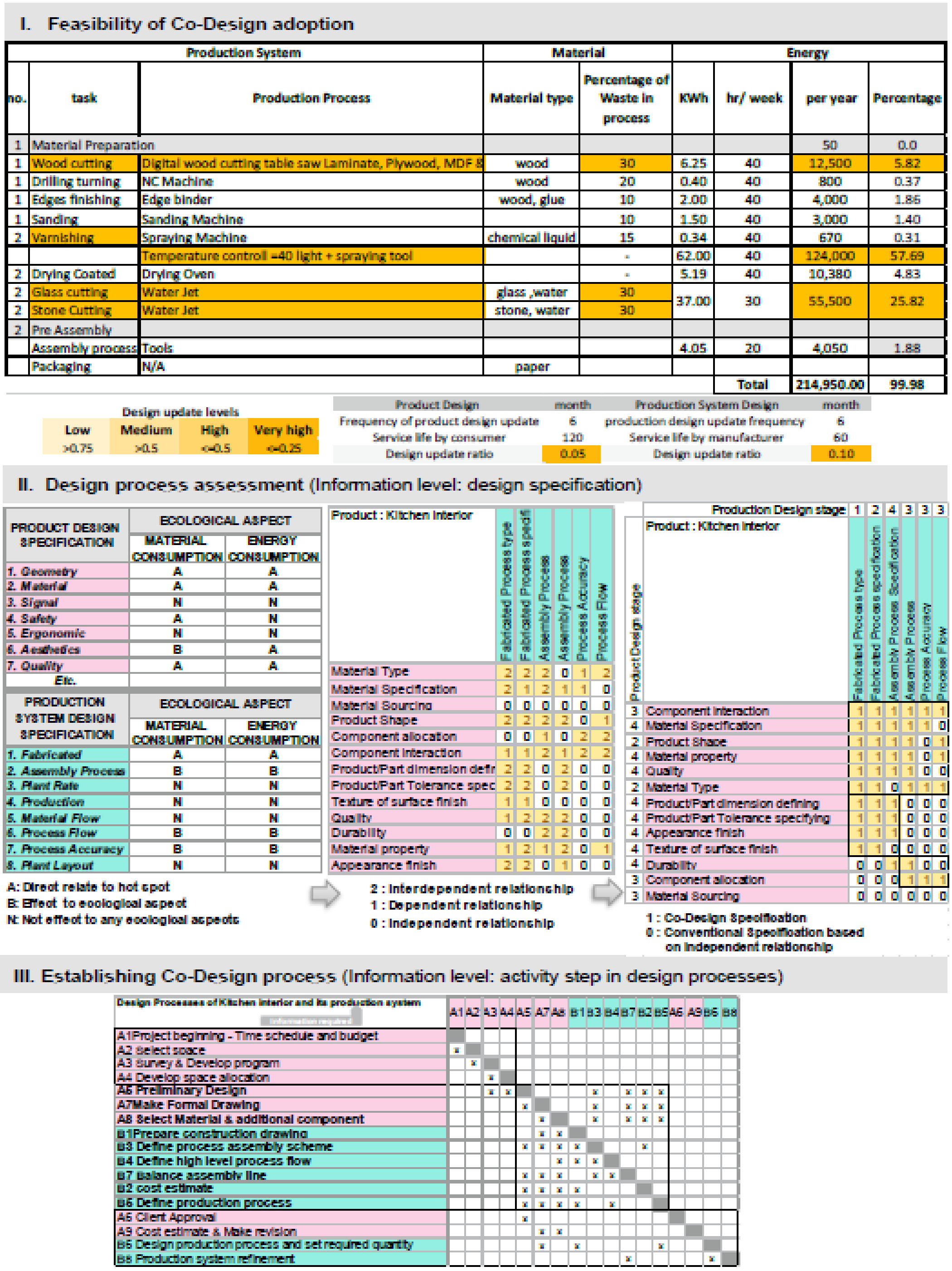
### IV: Supporting Co-Design Implementation

To support the implementation of new P&PS co-design process, this final step analyses existing/legacy design tools, guidelines and techniques to identify shortcomings and required updates, as well as defining the need for new capabilities and supporting tools. For instance, knowledge management model should be enhanced to emerge bidirectional P&PS information exchange through the support of interoperable computer integrated manufacturing and digitisation of manufacturing. Importantly, current information/knowledge sharing tools also require adjustment to provide timely accessibility to various designers within a P&PS co-design process, and further tool development and training of staff more effective communication and collaboration may be required.

## 6. Visualising the Benefit of Sustainable Co-Design of P&PS through an Example Product

The proposed co-design is expected to support manufacturers facing the modern challenges such as ever-changing demand, shorter product life, more frequent product updates, and customization requirements, as well as contemporary pressures for 'doing more with less' and adopting the most resource efficient approach to design and manufacture of their products. An example study for designing kitchen unites is used in Fig.6 to demonstrate the application of the co-design model and its potential benefits. Due to the high variety of customer requirements, a kitchen design can be considered a customised or even a personalised product. The data for this case study is synthesised based on the survey of products and production processes within actual industrial applications.

During the initial co-design feasibility study (see Fig.6), the values for design update ratio (calculated based on the frequency of design update and service life) for both products and production systems are found to be relatively high at 0.05 and 0.10 (suitable ratio for applying co-design is set to less than or equal 0.50), and wood varnishing is denoted as a high energy consuming process (with 57.69% of total energy consumption for the entire process).



## I. Feasibility of Co-Design adoption

| Production System | | | Material | | Energy | | | |
|---|---|---|---|---|---|---|---|---|
| no. | task | Production Process | Material type | Percentage of Waste in process | KWh | hr/ week | per year | Percentage |
| 1 | Material Preparation | | | | | | 50 | 0.0 |
| 1 | Wood cutting | Digital wood cutting table saw Laminate, Plywood, MDF 8 | wood | 30 | 6.25 | 40 | 12,500 | 5.82 |
| 1 | Drilling turning | NC Machine | wood | 20 | 0.40 | 40 | 800 | 0.37 |
| 1 | Edges finishing | Edge binder | wood, glue | 10 | 2.00 | 40 | 4,000 | 1.86 |
| 1 | Sanding | Sanding Machine | | 10 | 1.50 | 40 | 3,000 | 1.40 |
| 2 | Varnishing | Spraying Machine | chemical liquid | 15 | 0.34 | 40 | 670 | 0.31 |
| | | Temperature controll =40 light + spraying tool | | - | 62.00 | 40 | 124,000 | 57.69 |
| 2 | Drying Coated | Drying Oven | | - | 5.19 | 40 | 10,380 | 4.83 |
| 2 | Glass cutting | Water Jet | glass ,water | 30 | 37.00 | 30 | 55,500 | 25.82 |
| 2 | Stone Cutting | Water Jet | stone, water | 30 | | | | |
| 2 | Pre Assembly | | | | | | | |
| | Assembly process | Tools | | | 4.05 | 20 | 4,050 | 1.88 |
| | Packaging | N/A | paper | | | | | |
| | | | | | | Total | 214,950.00 | 99.98 |

Design update levels

| Low | Medium | High | Very high |
|---|---|---|---|
| >0.75 | >0.5 | <=0.5 | <=0.25 |

| Product Design | month | Production System Design | month |
|---|---|---|---|
| Frequency of product design update | 6 | production design update frequency | 6 |
| Service life by consumer | 120 | Service life by manufacturer | 60 |
| Design update ratio | 0.05 | Design update ratio | 0.10 |

## II. Design process assessment (Information level: design specification)

| PRODUCT DESIGN SPECIFICATION | ECOLOGICAL ASPECT | |
|---|---|---|
| | MATERIAL CONSUMPTION | ENERGY CONSUMPTION |
| 1. Geometry | A | A |
| 2. Material | A | A |
| 3. Signal | N | N |
| 4. Safety | A | N |
| 5. Ergonomic | N | N |
| 6. Aesthetics | B | A |
| 7. Quality | A | A |
| Etc. | | |

| PRODUCTION SYSTEM DESIGN SPECIFICATION | ECOLOGICAL ASPECT | |
|---|---|---|
| | MATERIAL CONSUMPTION | ENERGY CONSUMPTION |
| 1. Fabricated | A | A |
| 2. Assembly Process | B | B |
| 3. Plant Rate | N | N |
| 4. Production | N | N |
| 5. Material Flow | N | N |
| 6. Process Flow | B | B |
| 7. Process Accuracy | B | B |
| 8. Plant Layout | N | N |

A: Direct relate to hot spot
B: Effect to ecological aspect
N: Not effect to any ecological aspects

| Product : Kitchen Interior | Fabricated Process type | Fabricated Process specifi | Assembly Process | Assembly Process | Process Accuracy | Process Flow |
|---|---|---|---|---|---|---|
| Material Type | 2 | 2 | 2 | 0 | 1 | 2 |
| Material Specification | 2 | 1 | 2 | 1 | 1 | 0 |
| Material Sourcing | 0 | 0 | 0 | 0 | 0 | 0 |
| Product Shape | 2 | 2 | 2 | 2 | 0 | 1 |
| Component allocation | 0 | 0 | 1 | 0 | 2 | 2 |
| Component interaction | 1 | 1 | 2 | 1 | 2 | 2 |
| Product/Part dimension defir | 2 | 2 | 0 | 2 | 0 | 0 |
| Product/Part Tolerance spec | 2 | 2 | 0 | 2 | 0 | 0 |
| Texture of surface finish | 1 | 1 | 0 | 0 | 0 | 0 |
| Quality | 1 | 2 | 2 | 2 | 0 | 0 |
| Durability | 0 | 0 | 2 | 2 | 0 | 0 |
| Material property | 1 | 2 | 1 | 2 | 0 | 1 |
| Appearance finish | 2 | 2 | 0 | 1 | 0 | 0 |

2 : Interdependent relationship
1 : Dependent relationship
0 : Independent relationship

| | Production Design stage | 1 | 2 | 4 | 3 | 3 | 3 |
|---|---|---|---|---|---|---|---|
| Product Design stage | Product : Kitchen Interior | Fabricated Process type | Fabricated Process specification | Assembly Process Specification | Assembly Process | Process Accuracy | Process Flow |
| 3 | Component interaction | 1 | 1 | 1 | 1 | 1 | 1 |
| 4 | Material Specification | 1 | 1 | 1 | 1 | 1 | 0 |
| 2 | Product Shape | 1 | 1 | 1 | 1 | 0 | 1 |
| 4 | Material property | 1 | 1 | 1 | 1 | 0 | 1 |
| 4 | Quality | 1 | 1 | 1 | 1 | 0 | 0 |
| 2 | Material Type | 1 | 1 | 0 | 1 | 1 | 1 |
| 4 | Product/Part dimension defining | 1 | 1 | 1 | 0 | 0 | 0 |
| 4 | Product/Part Tolerance specifying | 1 | 1 | 1 | 0 | 0 | 0 |
| 4 | Appearance finish | 1 | 1 | 1 | 0 | 0 | 0 |
| 4 | Texture of surface finish | 1 | 1 | 0 | 0 | 0 | 0 |
| 4 | Durability | 0 | 0 | 1 | 1 | 0 | 0 |
| 3 | Component allocation | 0 | 0 | 0 | 1 | 1 | 1 |
| 3 | Material Sourcing | 0 | 0 | 0 | 0 | 0 | 0 |

1 : Co-Design Specification
0 : Conventional Specification based on Independent relationship

## III. Establishing Co-Design process (Information level: activity step in design processes)

| Design Processes of Kitchen interior and its production system<br>Information required | A1 | A2 | A3 | A4 | A5 | A7 | A8 | B1 | B3 | B4 | B7 | B2 | B5 | A6 | A9 | B6 | B8 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| A1Project beginning - Time schedule and budget | ■ | | | | | | | | | | | | | | | | |
| A2 Select space | x | ■ | | | | | | | | | | | | | | | |
| A3 Survey & Develop program | | x | ■ | | | | | | | | | | | | | | |
| A4 Develop space allocation | | | x | ■ | | | | | | | | | | | | | |
| A5 Preliminary Design | | | x | x | ■ | | | | x | | x | x | x | | | | |
| A7Make Formal Drawing | | | | | x | ■ | | | x | | x | x | x | | | | |
| A8 Select Material & additional component | | | | | | x | ■ | | x | | x | x | x | | | | |
| B1Prepare construction drawing | | | | | | x | x | ■ | | | | | | | | | |
| B3 Define process assembly scheme | | | | | x | x | x | x | ■ | | | x | | | | | |
| B4 Define high level process flow | | | | | | | x | x | x | ■ | | | | | | | |
| B7 Balance assembly line | | | | | x | x | x | | x | x | ■ | | | | | | |
| B2 cost estimate | | | | | x | x | x | x | | | | ■ | | | | | |
| B6 Define production process | | | | | x | x | x | x | | x | | | ■ | | | | |
| A6 Client Approval | | | | | x | | | | | | | | | ■ | | | |
| A9 Cost estimate & Make revision | | | | | | x | x | | | | | | | | ■ | | |
| B6 Design production process and set required quantity | | | | | | x | | x | | | | | x | | | ■ | |
| B8 Production system refinement | | | | | | | | | | | x | | | | | x | ■ |

Fig. 6 . Illustrating Feasibility of Co-Design, Assessment of P&PS Relationship and Co-design Processes Establishment

Therefore, in the second step, an interdependent relationship between the product and production system design processes is defined to address the requirements for frequent design updates (note that in relationship evaluation, values of 0, 1, and 2 are assigned to independent, dependent, and interdependent relationships respectively). Consequently, as part of co-design specifications material property and type, product geometry and quality, and part interactions within part design must be considered at the same time as specification of fabrication processes. In addition, part tolerance, appearance, and texture of the final product are simultaneously considered with specification for fabrication and assembly process types. Based on these relationships identified among product and production system design processes, a new set of combined co-design processes are developed using a Design Structured Matrix approach [14]. With this new co-design model, kitchen designers can visualise the effect of their product design changes on the production system in every project. Moreover, they can also reduce high energy consumption during wood varnishing through considerations for material minimisation (reducing the usage of varnished wood), selection of substitute materials such as glass or stone, or redesigning the varnishing process.

## 7. Conclusion

This study has addressed the requirement for a seamless integration in the design of products and their associated production systems. This sustainable co-design model is proposed specifically to unlock the potential of design processes to enhance resource efficiency within manufacturing applications. Other potential benefits associated to this approach include responsiveness to changing demand and requirement for product customization. Modern manufacturers with demand for frequent product design updates and the need for adopting rapidly evolving new production technologies will particularly benefit from the implementation of such co-design processes. The future research will focus on a further case study on a complex product to improve the application of this proposed approach and, generation of novel supporting toolkit to improve the cooperation and collaboration among interdependent design teams responsible for development of P&PS.

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