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The Sustainable Co-Design of Products and Production Systems

P. Lumsakul[a] *, L. Sheldrick[b], S. Rahimifard[a]

[a]Centre for Sustainable Manufacturing and Recycling Technologies (SMART), Loughborough University, Loughborough, UK
[b]Dyson School of Design Engineering, Imperial College London, London, UK

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.

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

* Corresponding author. Tel.: +44(0)1509 225401
E-mail address: p.lumsakul@lboro.ac.uk

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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

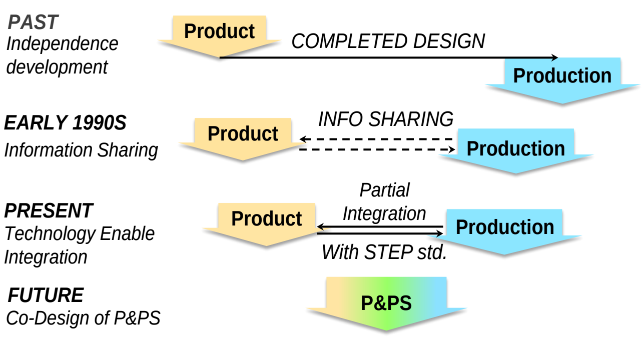

Fig. 1. The proposed evolution of sustainable co-design

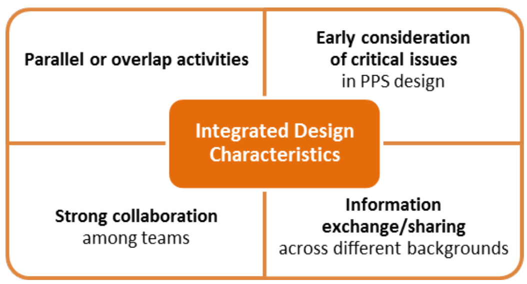

Fig. 2. Four main characteristics of the integrated design concepts

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.

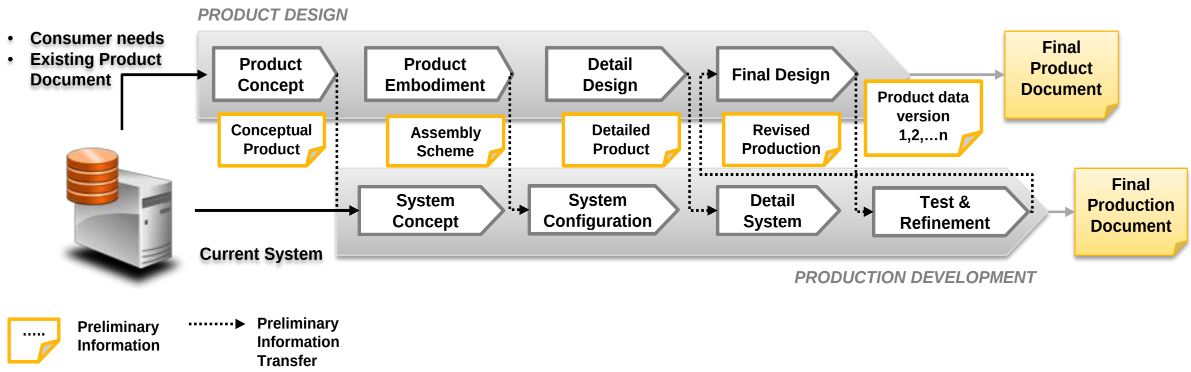

Fig. 3. The relationship of design processes of products and production systems

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.

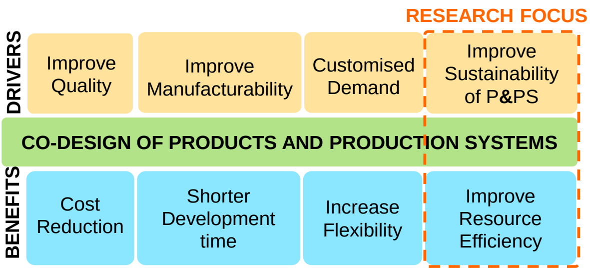

Fig. 4. Drivers and benefits of co-design of P&PS

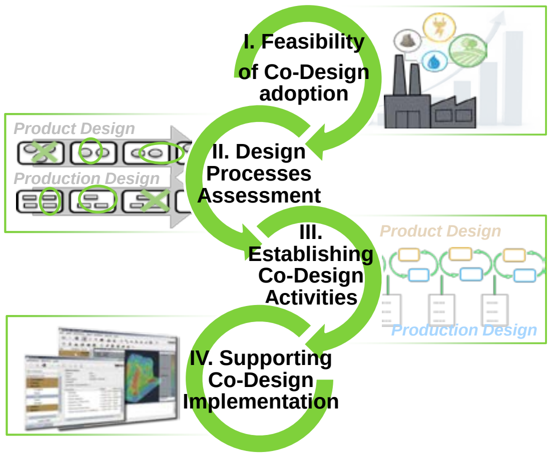

Fig. 5. The Sustainable Co-Design of Products and Production Systems

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 &	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	ECOLOGICAL ASPECT: 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	ECOLOGICAL ASPECT: 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 specific	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

Product Design stage	Production Design stage	1	2	4	3	3	3
	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 (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				■					
B5 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.

References

[1] Sheldrick L., Rahimifard S., Evolution in Ecodesign and Sustainable Design Methodologies, . *In: Nee A., Song B., Ong SK.(eds) Re-engineering Manufacturing for Sustainability.* Springer, Singapore, 2013; 35-40.

[2] Haapala K. R., Zhao F., Camelio J., Sutherland J. W., Skerlos S. J, Dornfeld D. A., Jawahir I. S., Clarens A. F.and. Rickli J. L, A Review of Engineering Research in Sustainable Manufacturing, *Journal of Manufacturing Science and Engineering* 2013;135:(041013)1-16.

[3] Tomiyama T., Gu P., Jin Y., Lutters D., Kind C. and Kimura F., Design Methodologies: Industrial and educational applications, *CIRP Annuals - Manufacturing Technologies*. 2009;58:543-565.

[4] Stoffels P., Vielhaber M., Methodical support for concurrent engineering across product and production (system) development, In: *Proceedings of the 20th International Conference on Engineering Design (ICED 15),* Design for X, Milan, Italy, 27-30.07.2015;4:1-8.

[5] Otto K., Wood K., Product Design: *Techniques in Reverse Engineering and New Production Development,* New Jersey: Prentice Hall, 2001.

[6] Winner R., Pennell J., Bertrand H. and Slusarczuk M., *The Role of Concurrent Engineering in Weapons Acquisition*., Institute of Defense Analyses., Alexandria, Virginia, 1988.

[7] Boothroy. G, Dewhurst P.,Knight W.A. *Product design for manufacture and assembly*, 3rd ed., New York: Marcel Dekker, c2011.

[8] Lu S.C-Y, Elmaraghy W., Schuh G., Wilhelm R. A Scientific Foundation of Collaborative Engineering. *CIRP Annals - Manufacturing Technology* 2007; 56:605-634.

[9] Mountney S., GAO J., Wiseall S. A knowledge system to support manufacturing knowledge during preliminary design. *International Journal of Production Research*. 2007; 45(7): 1521-1537.

[10] Tolio T., Ceglarek D., ElMaraghy HA., Fischer A., Hu S.J., Laperrie` re L., Newman S.T, Va´ncza J. SPECIES—Co-evolution of products, processes and production systems. *CIRP Annals - Manufacturing Technology* 2010; 59: 672-693.

[11] Büyüközkan G., Arsenyan J. Collaborative product development: a literature overview. *Production Planning & Control – The Management of Operations*. 2012; 23(1):47-66.

[12] Maier A.M., Kreimeyer M., Hepperle C., Eckert C.M., Lindemann U, Clarkson P.J. Exploration of Correlations between Factors Influencing Communication in Complex Product Development. *Concurrent Engineering*. 2011;16(1):37-59.

[13] Arundachawat P., Roy R., Al-Ashaab A., Shehab E. Design Rework Prediction in Concurrent Environment: Current Trends and Future Research Directions *In: Proceedings of the 19th CIRP Design Conference-Competitive Design*, Cranfield, 2009

[14] Magrab E., Gupta S., MacCluskey F. and Sandborn P., *Integrated product and process design and development-the product realization process*,second edition, Boca Raton, Florida: CRC Press, 2009.

[15] Danilovic M., Browning T.R. "Managing complex product development projects with design structure matrices and domain mapping matrices" *International Journal of Project Management.* 2007;25(3):300-314.