PRODUCT FAMILY ARCHITECTURE: A CASE STUDY ON THE DESIGN OF A FLOOR LEVEL PALLETIZER

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Abstract: Given the challenge currently imposed by mass customization (MC) requirements to the new product development (NPD), companies of the capital goods industry (CGI) have been forced to optimize its external variety in the face of the internal complexity resulting from product differentiation. Practitioners of the CGI recognize that product family design and platform-based product development are useful tools to accomplish such trade-off. However, less than 6% of the publications in this field cover applications in this industry. The purpose of this article is to investigate how to implement an MC strategy in the CGI from a product development perspective. The research method is the single-case study. The case relates the application of the product family architecture methodology (PFA) in the development of a floor level palletizer product family (FLPPF). The main results of the research are the conceptual design of an FLPPF, a qualitative analysis on the effectiveness of the PFA method in the development of FLPPF, and the identification of gaps in the theory that might be useful for future research.

Keywords: mass customization, product family, product platform, capital goods.

1. INTRODUCTION

Mass customization (MC) is a production strategy which aims to satisfy individual customer needs by introducing personalized products and services while taking advantage of mass production efficiency (Pine, 1993). Since the late 1980s, MC has received many attention and popularity in industry and academia alike (Jiao & Tseng, 1999). Studies, e.g., Da Silveira et al. (2001) and Fogliatto et al. (2012) have reported a significant increase in MC publications in the last two decades. In July of 2017, a search by the title, abstract or keywords in Science Direct database, the term "mass customization" yielded 255 articles from 2010 in, which represents an increase of 80% if compared to the previous ten years.

Currently, consumers demand high-quality, low-priced, and customized products at the same time. Therefore, the competition among firms is no longer a single-attribute competition by price, turning into a multi-attribute competition by variety, quality, dependability, and time to market simultaneously (Jiao & Tseng, 1999). To compete in this multi-attribute marketplace, manufacturers expanded their product portfolio based on the assumption that a larger product variety would drive sales and generate additional revenue (Ho & Tang, 1998). However, a greater product range usually implies in a substantive reduction of efficiency (Salvador et al., 2002). In the face of this trade-off, companies decide to optimize its external variety regardless the internal complexity resulting from product differentiation (Jiao et al., 2007).

Companies recognize that product family design and platform-based product development are useful tools to provide sufficient product variety and at the same time maintaining a high production scale (Meyer & Utterback, 1993; Sundgren, 1999). Product platform is a group of subsystems and interfaces developed to form a standard structure to design and produce a stream of derivative products (Meyer & Lehnerd, 1997). Product family refers to a set of similar products that are derived from a common platform and yet possess specific features to meet particular customer requirements (Meyer & Lehnerd, 1997). Owing to the flurry of research activities, this field has matured rapidly in the past decade, and numerous industrial applications succeed to involve product family and platform design (Simpson et al., 2014). According to Fetterman (2013), cases studies illustrate the major part of these applications, and less than 6% cover applications in the capital goods industry (CGI). In this industry, usually, decisions made before the release of a product design to manufacturing are responsible for up to 85% of the cost (Rozenfeld et al., 2006), which reinforces the importance of the design stage in the manufacturing competitiveness.

The research question this study poses is: how to implement an MC strategy in the CGI from a product development perspective? The purpose of this article is to implement an MC strategy in a CGI company. As an alternative answer to the research question, Jiao and Tseng (1999) first introduced a framework of design for mass customization (DFMC) based on the product family architecture (PFA). Starting from this assumption, the first specific objective of this article is to apply the PFA methodology in the development of a floor level palletizer product family (FLPPF). The second specific objective is analyzing the feasibility of the application, comparing empirical results with elements theoretical retrieved from relevant literature theory on product development process (PDP). The research method is the single-case study. The case relates the application of the PFA methodology in the development of an FLPPF, limited to the concept development and system-level design phases of PDP (Ulrich & Eppinger, 2000). The data used in the subsequent analysis came from palletizing projects performed by a Brazilian manufacturer, and from the website of three world-leading competitors in this market.

2. PRODUCT FAMILY ARCHITECTURE (PFA) METHODOLOGY

The development of PFA consists of three consecutive stages. They are (i) customer requirement analysis in the functional view, (ii) modularization of technological solutions in the technical view, and (iii) economic evaluation of building blocks in the physical view (Jiao & Tseng, 1999).

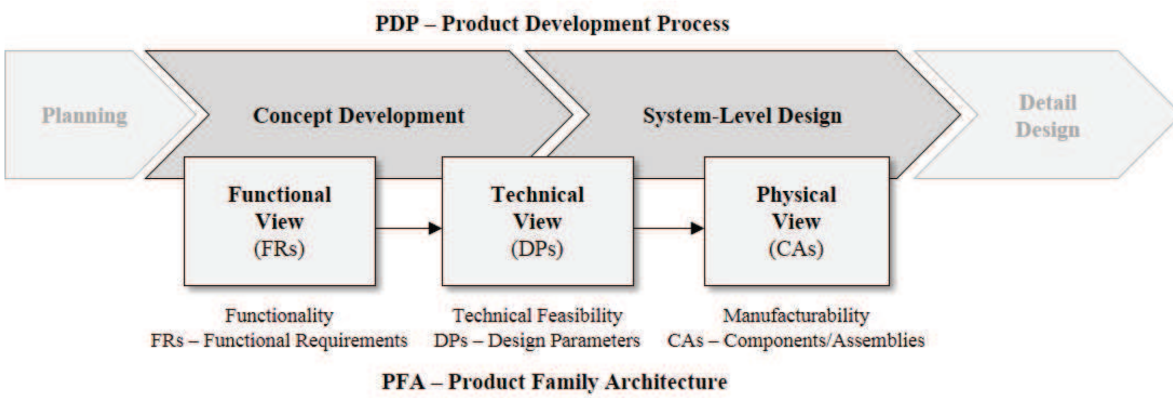


Fig. 1. PFA-views of product modeling. Adapted from (Jiao, 1998; Ulrich & Eppinger, 2000).

2.1 Functional View

The functional view of a PFA starts from the inductive formulation of functional requirements (FRs) based on existing product portfolio. Product strategies are then proactively assessed to refine the FRs regarding the marketability enhancement of product offerings. The next step is the establishment of FRs hierarchy, followed by the mapping of existing products specifications into various FRs instances (FR*s). Since the formulated

FRs are generic to all the customers, it is necessary to categorize them into specific customer groups (CGs). A relative importance analysis is needful to extract key FRs for characterizing different CGs. The classification of various FR*s for a particular CG defines the functional classification. The focus of functional classification is the commonality analysis through clustering similar FR*s into clusters. In the planning of a product family design, the determination of the target value for an FR* results from domain knowledge based on understanding the characteristics of the clustered class. Usually, various FR*s values within the same cluster are averaged to obtain the target FR value for a planned product variant.

A combined decomposition/classification tree (DCT) is adopted to represent the functional view of a product family from an abstract level to individual instances. There are two types of tree structures in a DCT. One is the decomposition tree adopted to represent the FR hierarchy, where each node represents an FR with its sub-FRs breakdown. The other one is the classification tree used to describe different instances of every FR. Analytical techniques such as Pareto Analysis, Analytical Hierarchy Process (AHP) (Satty, 1991) and Fuzzy Clustering Analysis (FCM) (Bezdec, 1981; Gath & Geva, 1989; Gu & Dubuisson, 1990) integrate the framework of PFA functional view.

In summary, the functional modeling of a PFA sets the targets for product family design. Customer grouping determines the type of target product family, where different customer groups are projected to distinct product families. Functional classification of a particular CG gives rise to the target product variants within the product family.

Fig. 2 shows the framework of PFA functional view.

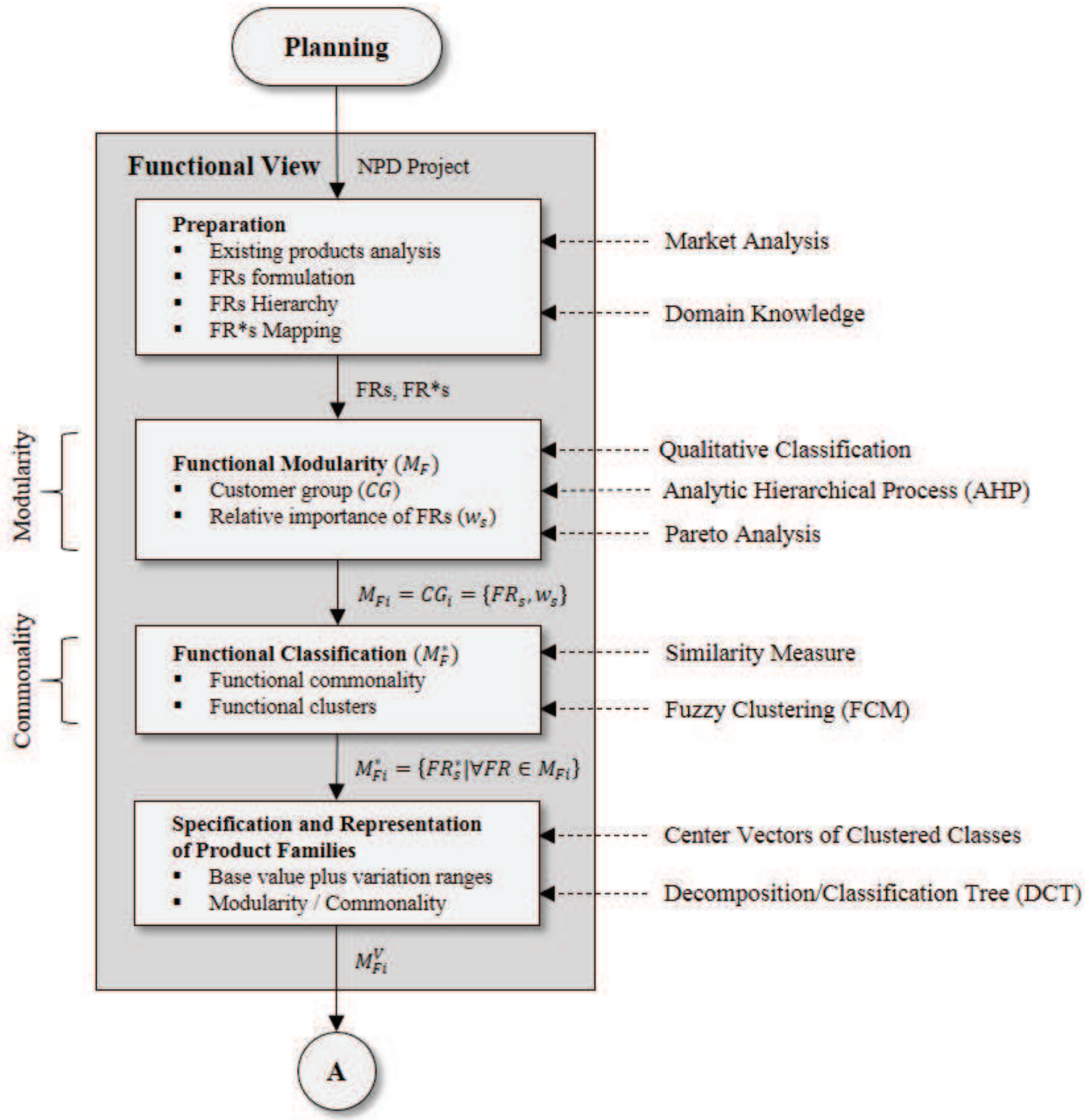


Fig. 2. Flowchart of functional view. Adapted from (Jiao, 1998; Rozenfeld, 2006; Suh, 2000).

2.2 Technical View

From the generic FRs formulated in the functional view and the solution technologies applied to existing products, the technical view identifies the design parameters (DPs) that better fulfills the FRs. A DPs hierarchy represents all the DPs and its interrelationships.

Based on the understanding of the solution principles, the utilization of a design matrix helps to depict the mapping relationships between FRs and DPs (Suh, 1990). In practice, design matrices are often coupled (Johannesson, 1997), and the technical modularity tries to decompose such couplings into smaller logic units, i.e., design modules (DMs). Matrix decomposition techniques are used for that purpose (Pimmler and Eppinger, 1994). As a result, FRs-DPs cells or clusters, indicate the boundaries among different DMs. Also, the overlapping elements show the interfacing relationships between DMs, which often results in trade-offs in design decision making.

After the identification of DMs, the next step is the definition of the modular structure, which represents the overall schematic of arranging these DMs for design configuration. In establishing a modular structure, the working principle of a solution technology is of particular concern in determining how to fit DMs into the structure. Usually, such a work heavily depends on sophistic domain knowledge.

Similar to the functional classification, the focus of design instantiation is the commonality analysis through clustering similar design parameter instances (DP*s) into clusters. These clusters are then characterized by a base value and its variation range.

The representation of a DM (building block regarding DPs) involves both its functional and structural aspects. A class-member relationship applies to characterize the differentiation between building block class (BB_k) and building block instance $\left(BB_{k\_j}\right)$. While BB_k derives from the type of FRs-DPs mapping, the BB_{k_j} comes from different instances of a particular mapping. The DCT is also used to describe both in a single formalism.

In summary, corresponding to each CG identified in the functional view of a PFA, the technical view reveals the application of technology, i.e., solution principle, to a product design and describes the product design by its modules and the modular structure.

Fig. 3 shows the framework of PFA technical view.

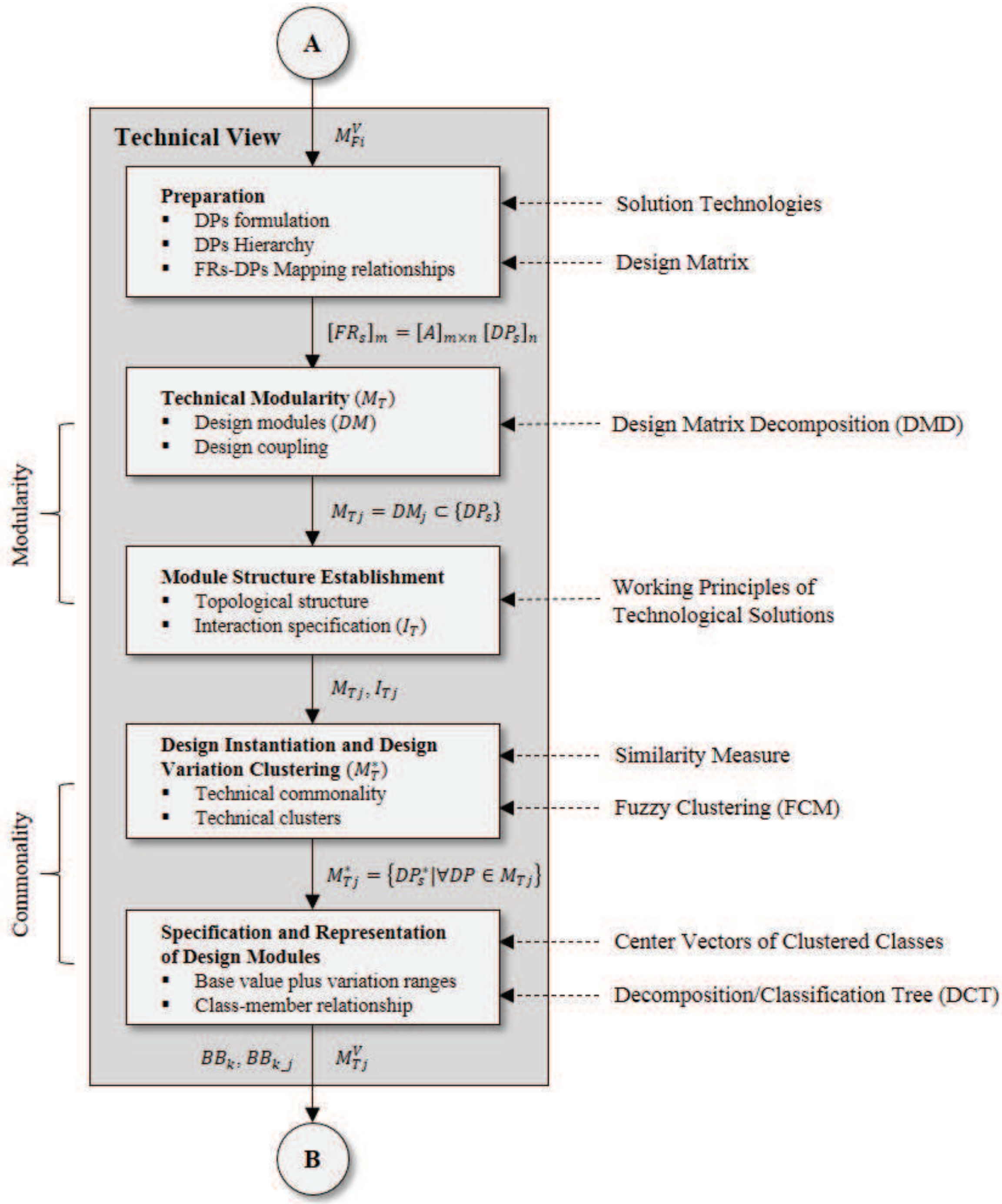


Fig. 3. Flowchart of technical view. Adapted from (Jiao, 1998; Suh, 2000).

2.3 Physical View

In physical modeling, the technical modularity is performed regarding physical product structures. For each DM identified in the technical view, the corresponding components and assembly structures (CAs) are determined according to available process capabilities and concerning existing products. In physical modularity, the physical interaction between CAs plays an important role. An interaction matrix is first formed regarding pairwise analysis between CAs interactions. Then the Interaction Matrix Analysis (IMA) (Pimmler & Eppinger, 1994) technique is applied to identify candidate physical modules. A DM (building block regarding DPs) is possible to be accomplished by more than one physical module (building block regarding CAs). The next issue is to select suitable physical modules (PM) for a particular DM through economic evaluation.

The purpose of the economic evaluation is to position multiple PMs according to their contribution to maintaining the economy of scale and providing functional variety. In other words, the common denominators should be maximized only for those PMs that are both utility-important to the customers and cost-effective. The model used for expressing customers' expectations on products in PFA is the Utility Analysis (Yoshimura and Takeuchi, 1994). For costing estimation, PFA adopts the utilization of a Pragmatic Approach for Product Costing (Tseng and Jiao, 1997a). The evaluations against technical and economic criteria lead to pair-wise overall ratings for PMs.

With multiple PMs identified for each product family, the usage of a configuration structure helps in the establishment of end product configuration. A configuration structure of a product family describes how different products variants derived from the combination of the PMs and the interconnections across varying levels of assembly. A Polyhierarchical Node-arc Graph (Kohlhase & Birkhofer, 1996) is used for that purpose.

In summary, the physical model consists of various types of CAs to realize different technological solutions in the technical view. In addition to the mapping relationships of FR-DP-CA, a significant concern associated with the physical view is the economic evaluation of the granularity trade-off among various CAs options according to available process capabilities of a firm.

Fig. 4 shows the framework of PFA physical view.

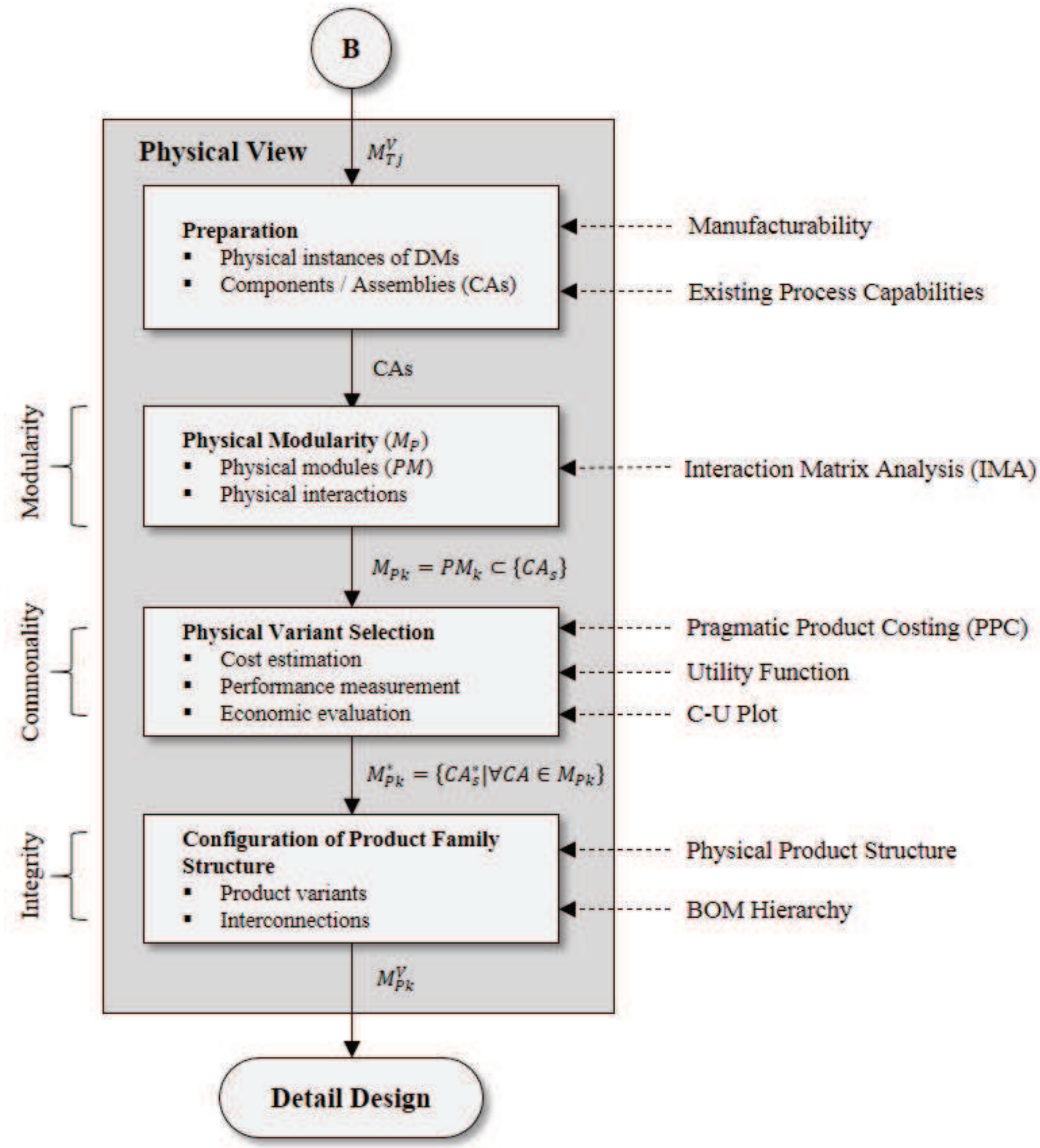


Fig. 4. Flowchart of physical view. Adapted from (Jiao, 1998; Suh, 2000).

3. THE RESEARCH: CASE STUDY

The research object is a palletizer. A palletizer is an automatic machine that builds unit loads by means of stacking products onto a pallet based on a predetermined pattern configuration and a given number of layers. Advancements in technology, requirements for higher speeds, the ability to handle different pallet patterns and the need for reducing workplace injuries are some of the customers' attributes that have been fostering the development of more efficient and flexible palletizers. The packing industry usually classifies the palletizers by types which include floor level palletizers, high-level palletizers, and robotic palletizers. For being considered smaller, more flexible in layout, safer, and simple to adapt to product changes for a lower purchase and space cost, this study used a floor level palletizer (FLP) to illustrate the application of PFA methodology in the CGI.

FLPs have an infeed entry level not higher than 1m. The product flows through on infeed conveyor, and before it moves to the row forming area, it is correctly oriented by a turning device. A complete row is then formed and pushed onto the layer forming area. A particular quantity of rows forms a layer, which after finished is moved forward to the stripper plate and then placed onto the pallet or previous layer. This process repeats cyclically until a pallet load is complete and transferred to the pallet discharge conveyor (Popple, 2009).

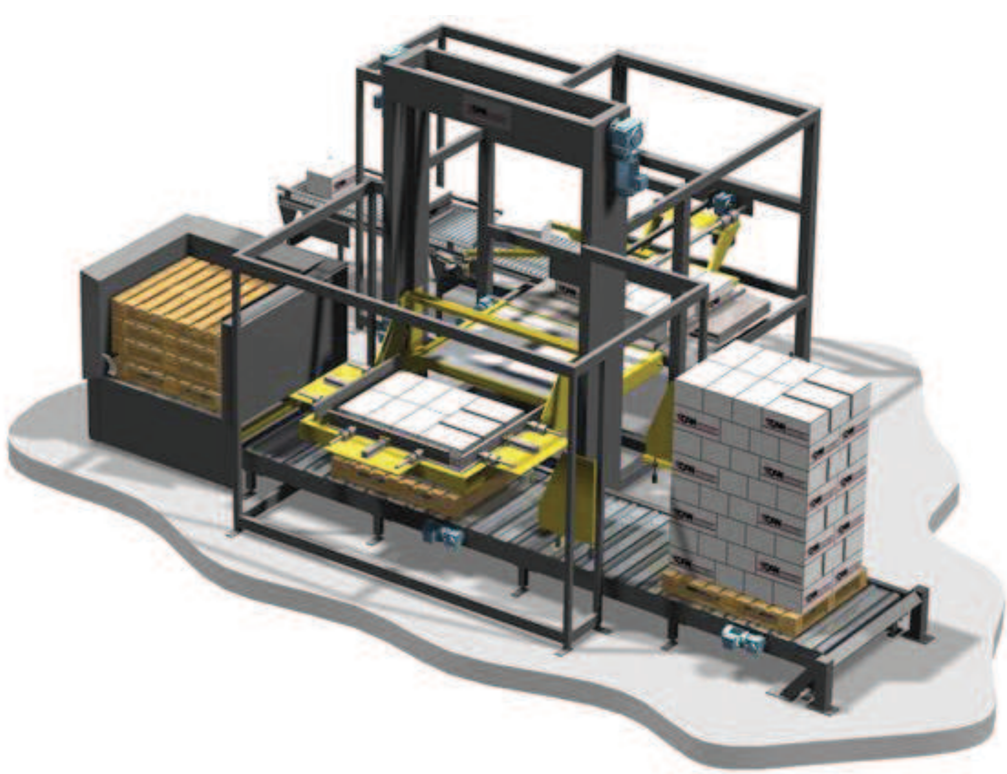


Fig. 5. An example of FLP. Captured from (Dan-Palletiser A/S).

3.1 Functional Modeling Through Customer Requirements

The FRs regarding FLPPF design were identified and formulated in a hierarchical form through the functional structure of the palletizing process in conjunction with comprehensive interviews with domain experts (Pahl, 2007). With the purpose of reducing the number of pairwise comparisons, the AHP was employed to weight the customer needs, then the House of Quality matrix was used to transfer the priorities of the customer needs into FRs. (Nakui, 1987). For illustrative simplicity, Table 1 shows only the FRs formulated for the consumer goods pallet assembly (CGPA). This category of CGPA resulted from the customer grouping procedure briefly described in Section 2.1.1.

Table 1. FRs hierarchy for consumer goods pallet assembly.

Generic level	*Terminology level*	*Engineering level*
FR0: Pallet Assembly	FR1: Secondary packaging (SP) handling	FR1.1: Hold SP buffer FR1.2: Singulate SP FR1.3: Orientate SP FR1.4: Identify SP
	FR2: Pallet (PLT) handling	FR2.1: Buffer PLTs FR2.2: Dispense PLT FR2.3: Move PLT to load position FR2.4: Align PLT into loading position (X-axis) FR2.5: Align PLT into loading position (Y-axis)
	FR3: Pallet pattern assembly	FR3.1: Build row FR3.2: Move row to layer position FR3.3: Build layer FR3.4: Move layer to load height FR3.5: Guarantee load alignment FR3.6: Place layer onto pallet/load
	FR4: Load handling	FR4.1: Print and apply load labeling FR4.2: Discharge load
	FR5: Stretch wrapping	FR5.1: Unwind the film FR5.2: Pre-stretch the film FR5.3: Wrap the film on the load perimeter FR5.4: Wrap the film along the load height FR5.5: Cut and seal the film
	FR6: Divider sheets (DS) handling	FR6.1: Buffer DSs FR6.2: Pick DS FR6.3: Move DS to load height FR6.4: Move DS to load position FR6.5: Place DS onto pallet/load
	FR7: Compliance	FR7.1: Safety: ISO 13849-1

According to these FRs, existing products specifications were instantiated into various FR instances (FR*s). The data utilized in FRs instantiation came from palletizing projects performed by a Brazilian manufacturer, and from the website of three world-leading competitors in this market. Since these FR*s vary widely due to several desired values and ranges for specific FRs, the functional classification procedure was applied to group similar customer specifications into clusters. Fig. 6 illustrates the FCM analysis performed for two different FRs using the software Matlab (Bezdec, 1981). A 99% confidence interval for each cluster was also calculated to evaluate the overlapping between adjacent clusters (Krishnamoorthi, 2011). The target values for each FR were determined for subsequent product family development based on experts' knowledge as a result of the understanding the characteristics of the clustered classes.

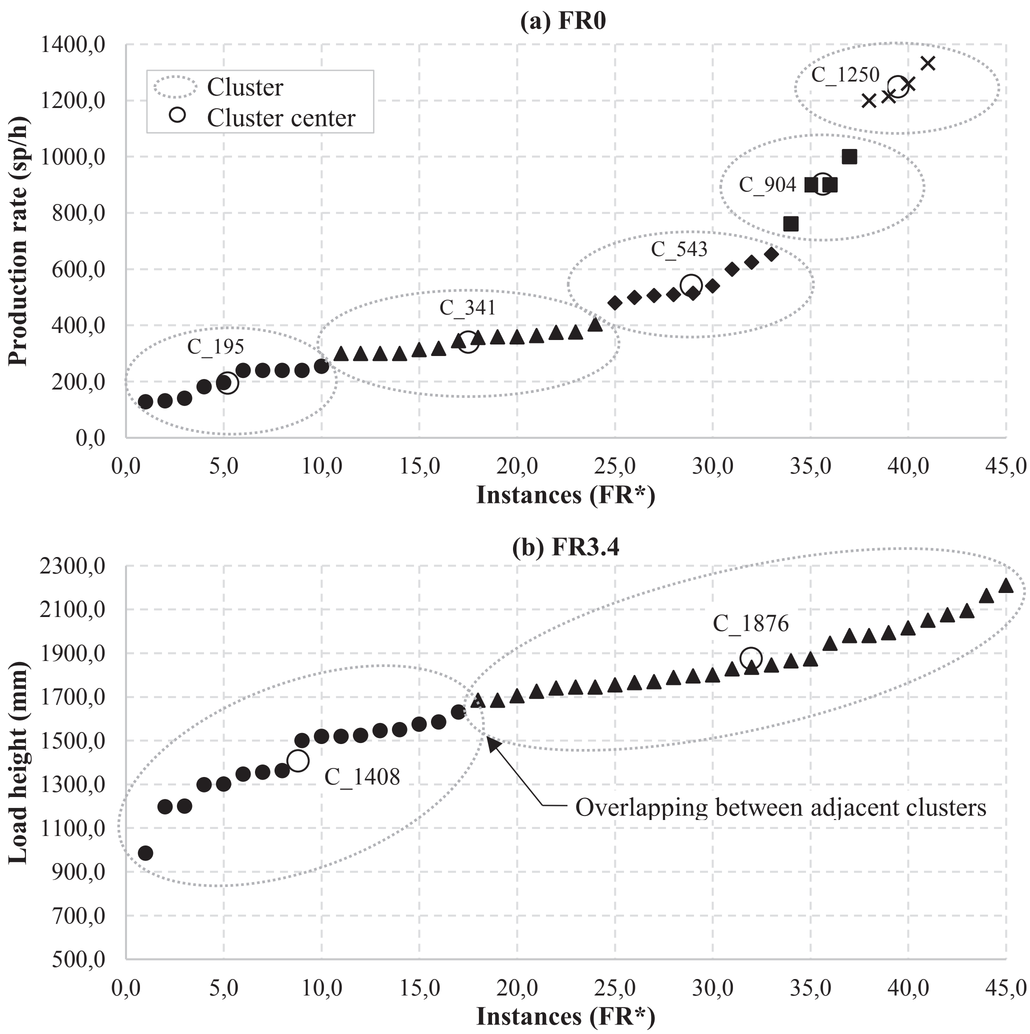


Fig. 6. An example of FR*s clustering using FCM algorithm.

With FRs target values defined through the functional classification, we used a DCT to represent the functional view of an FLPPF for CGPA, according to Fig.7.

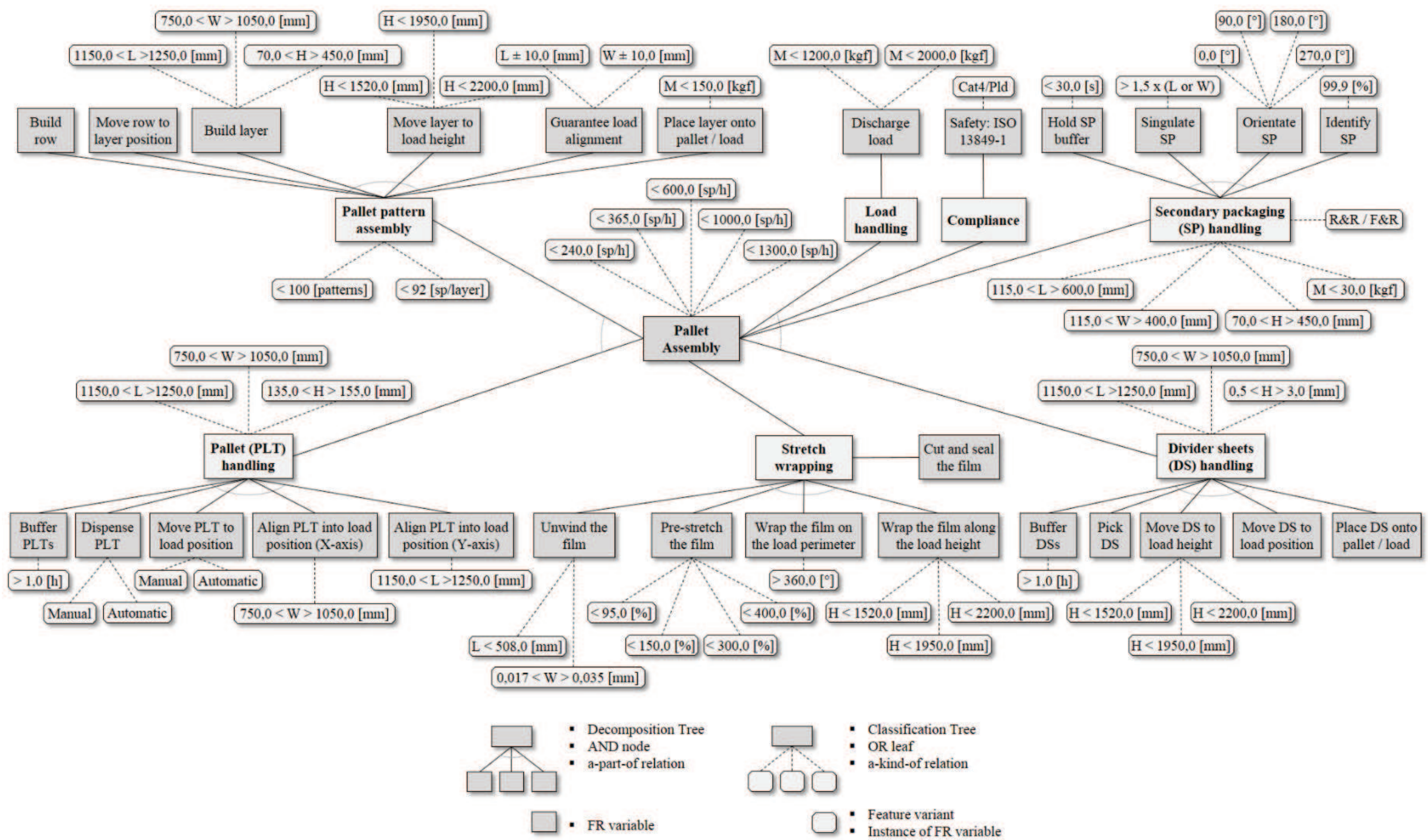


Fig. 7. DCT of an FLPPF for CGPA.

3.2 Technical Modeling Through Modularizing Technological Solutions

The available technologies for FLPs were investigated at this stage. There are two methods used to create a palletized load: row forming and inline (Popple, 2009). According to the entire target FRs of the customer group (CGPA) and considering technological trends and existing process capabilities, the row forming method was adopted in the development of FLPPF. With the solution technology determined and following the axioms of Axiomatic Design theory (Suh, 1990), the DPs were then formulated concerning FRs. Table 2 shows the results of DP formulation.

Table 2. DPs hierarchy for consumer goods pallet assembly.

First level		*Second level*		*Third level*	
DP0:	Palletizer topology	DP1:	Secondary packaging (SP) handling	DP1.1:	SP brake conveyor
				DP1.2:	SP singulation conveyor
				DP1.3:	SP turner
				DP1.4:	SP barcode reader
		DP2:	Pallet (PLT) handling	DP2.1:	PLTs magazine
				DP2.2:	PLT dispenser
				DP2.3:	PLT infeed conveyor
				DP2.4:	PLT cradle side guides
				DP2.5:	PLT cradle back stop
		DP3:	Pallet pattern assembly	DP3.1:	Row builder
				DP3.2:	Row elevator
				DP3.3:	Row puller
				DP3.4:	Layer elevator
				DP3.5:	Layer side guides
				DP3.6:	Layer back stop
				DP3.7:	Retractable roller floor
		DP4:	Load handling	DP4.1:	Load labeling
				DP4.2:	Load outfeed conveyor
		DP5:	Stretch wrapping	DP5.1:	Film dispenser
				DP5.2:	Film pre-stretch unit
				DP5.3:	Load turntable
				DP5.4:	Spool carriage
				DP5.5:	Film cutting and sealing unit
		DP6:	Divider sheets (DS) handling	DP6.1:	DS magazine
				DP6.2:	DS gripper
				DP6.3:	Vacuum pump
				DP6.4:	DS elevator
				DP6.5:	DS carriage
		DP7:	Frame	DP7.1:	Safety guarding
				DP7.2:	Maintenance doors
				DP7.3:	Light curtains

Based on the understanding of the solution principles, a design matrix was used to map the relationships between FRs and DPs. The algorithm developed by Kusiak and Chow (1987) was employed to decompose the design matrix into cells, from which design modules (DM) were induced (Fig. 8). Although the algorithm suggested the merging of modules DM3 with DM4, and DM5 with DM6, they were disjointed purposely to better fitting them into the technical solution. The representation of DMs is given in Table 3.

Design Matrix Decomposition

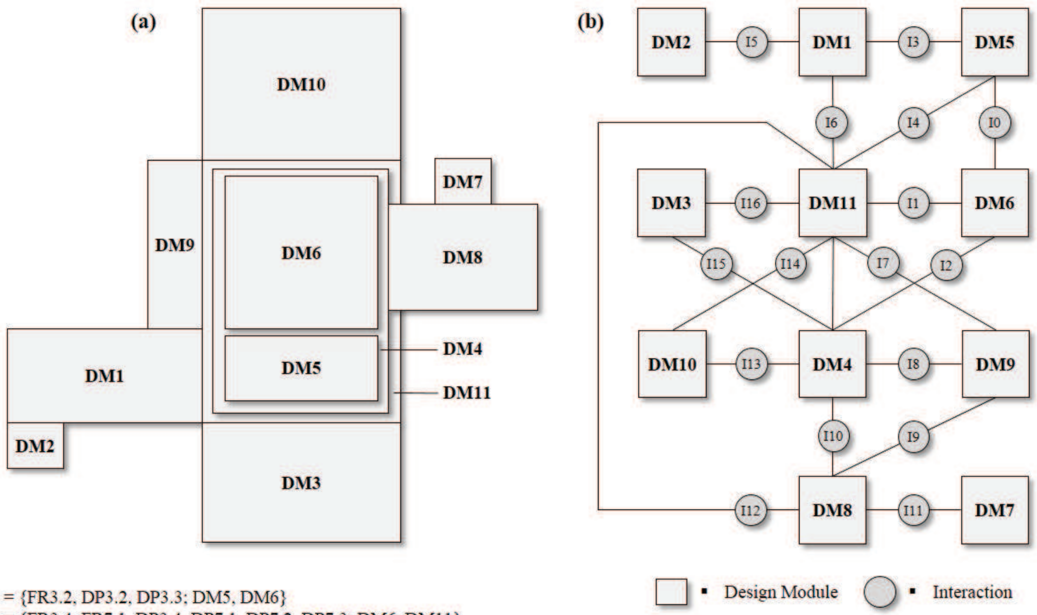
Functional Requirement (FR)	*Design Parameters (DP)*	DP1.1: SP brake conveyor	DP1.2: SP singulation conveyor	DP1.3: SP turner	DP1.4: SP barcode reader	DP2.1: PLTs magazine	DP2.2: PLT dispenser	DP2.3: PLT infeed conveyor	DP2.4: PLT cradle side guides	DP2.5: PLT cradle back stop	DP3.1: Row builder	DP3.2: Row elevator	DP3.3: Row puller	DP3.4: Layer elevator	DP3.5: Layer side guides	DP3.6: Layer back stop	DP3.7: Retractable roller floor	DP4.1: Load labeling	DP4.2: Load outfeed conveyor	DP5.1: Film dispenser	DP5.2: Film pre-stretch unit	DP5.3: Load turntable	DP5.4: Spool carriage	DP5.5: Film cutting and sealing unit	DP6.1: DS magazine	DP6.2: DS gripper	DP6.3: Vacuum pump	DP6.4: DS elevator	DP6.5: DS carriage	DP7.1: Safety guarding	DP7.2: Maintenance doors	DP7.3: Light curtains
Hold SP buffer	FR1.1: |1|																														
Singulate SP	FR1.2:	1	1																														
Orientate SP	FR1.3:	1	1	1																													
Identify SP	FR1.4:				1																										
Buffer PLTs	FR2.1:					1	1																									
Dispense PLT	FR2.2:					1	1																									
Move PLT to load position	FR2.3:							1																								
Align PLT into load pos. (X-axis)	FR2.4:					1		1	1																							
Align PLT into load pos. (Y-axis)	FR2.5:					1		1		1																						
Build row	FR3.1:										1	1																					
Move row to layer position	FR3.2:											1	1																				
Build layer	FR3.3:												1				1																
Move layer to load height	FR3.4:													1			1																
Guarantee load alignment	FR3.5:												1		1	1																	
Place layer onto pallet / load	FR3.6:												1	1	1	1	1																
Print and apply load labeling	FR4.1:																		1															
Discharge load	FR4.2:																		1														
Unwind the film	FR5.1:																			1	1													
Pre-stretch the film	FR5.2:																				1													
Wrap the film on the load perimeter	FR5.3:																			1	1	1												
Wrap the film along the load height	FR5.4:																				1	1	1											
Cut and seal the film	FR5.5:																					1		1										
Buffer DSs	FR6.1:																								1			1						
Pick DS	FR6.2:																								1	1	1	1	1			
Move DS to load height	FR6.3:																								1	1	1	1				
Move DS to load position	FR6.4:																									1	1		1			
Place DS onto pallet / load	FR6.5:																									1	1	1	1			
Safety: ISO 13849-1	FR7.2:																													1	1	1

Fig. 8. Design matrix decomposition for technical modularity.

Table 3. FLPPF design modules.

Design Modules (DMs)	*Functional Requirements (FRs)*	*Design Parameters (DPs)*
DM1: SP Infeed	FR1.1: Hold SP buffer FR1.2: Singulate SP FR1.3: Orientate SP	DP1.1: SP brake conveyor DP1.2: SP singulation conveyor DP1.3: SP turner
DM2: SP barcode reader	FR1.4: Identify SP	DP1.4: SP barcode reader
DM3: PLT dispenser	FR2.1: Buffer PLTs FR2.2: Dispense PLT FR2.3: Move PLT to load position FR2.4: Align PLT into load position (X-axis) FR2.5: Align PLT into load position (Y-axis)	DP2.1: PLTs magazine DP2.2: PLT dispenser DP2.3: PLT infeed conveyor
DM4: Base	FR2.4: Align PLT into load position (X-axis) FR2.5: Align PLT into load position (Y-axis)	DP2.4: PLT cradle side guides DP2.5: PLT cradle back stop
DM5: Row builder	FR3.1: Build row FR3.2: Move row to layer position	DP3.1: Row builder DP3.2: Row elevator
DM6: Layer builder	FR3.2: Move row to layer position FR3.3: Build layer FR3.4: Move layer to load height FR3.5: Guarantee load alignment FR3.6: Place layer onto pallet/load	DP3.3: Row puller DP3.4: Layer elevator DP3.5: Layer side guides DP3.6: Layer back stop DP3.7: Retractable roller floor
DM7: Load labeling	FR4.1: Print and apply load labeling	DP4.1: Load labeling
DM8: Load conveyor	FR4.2: Discharge load	DP4.2: Load outfeed conveyor
DM9: Stretch wrapping	FR5.1: Unwind the film FR5.2: Pre-stretch the film FR5.3: Wrap the film on the load perimeter FR5.4: Wrap the film along the load height FR5.5: Cut and seal the film	DP5.1: Film dispenser DP5.2: Film pre-stretch unit DP5.3: Load turntable DP5.4: Spool carriage DP5.5: Film cutting and sealing unit
DM10: DS dispenser	FR6.1: Buffer DSs FR6.2: Pick DS FR6.3: Move DS to load height FR6.4: Move DS to load position FR6.5: Place DS onto pallet/load	DP6.1: DS magazine DP6.2: DS gripper DP6.3: Vacuum pump DP6.4: DS elevator DP6.5: DS carriage
DM11: Frame	FR7.1: Safety: ISO 13849-1	DP7.1: Safety guarding DP7.2: Maintenance doors DP7.3: Light curtains

Fig. 9(b) graphically illustrates the topological structure of the FLP technological solution, where modules and their interrelationship are described explicitly. Interactions were specified not only according to their inter-cell elements in a decomposed design matrix but also through the arrangement of DMs into an FLP preliminary layout. (Fig. 9(a)). An interaction indicates that design coupling is involved between modules. A dummy interaction means that there exists no design coupling, but particular linkages resulting from the solution principle.



I0 = {FR3.2, DP3.2, DP3.3; DM5, DM6}
I1 = {FR3.4, FR7.1, DP3.4, DP7.1, DP7.2, DP7.3; DM6, DM11}
I2 = {FR3.5, FR3.6, DP2.4, DP2.5, DP3.4, DP3.5, DP3.6, DP3.7; DM4, DM6}
I3 = {FR3.1, DP1.3, DP3.1; DM1, DM5}
I4 = {FR3.2, FR7.1, DP3.2, DP7.1,DP7.2; DM5, DM11}
I5 = {Dummy interaction}
I6 = {FR7.1, DP7.1; DM1, DM11}
I7 = {FR7.1, DP7.1, DP7.2; DM9, DM11}
I8 = {FR2.4, FR2.5, FR5.3, DP2.4, DP2.5, DP5.3; DM4, DM9}
I9 = {FR4.2, DP4.2, DP5.3; DM8, DM9}
I10 = {FR4.2, DP2.4, DP2.5, DP4.2; DM4, DM8}
I11 = {Dummy interaction}
I12 = {FR4.2, FR7.1, DP4.2, DP7.3; DM8, DM11}
I13 = {FR6.4, FR6.5, DP2.4, DP2.5, DP6.2, DP6.4, DP6.5; DM4, DM10}
I14 = {FR6.3, FR7.1, DP6.4, DP7.1, DP7.2; DM10, DM11}
I15 = {FR2.3, FR2.4, FR2.5, DP2.3, DP2.4, DP2.5; DM3, DM4}
I16 = {FR7.1, DP2.3, DP7.1; DM3, DM11}

Fig. 9. (a) FLP preliminary layout; **(b)** topological structure.

Each DP can be accomplished by more than one working principle. The combination of these working principles into working structures leads to the solution principle, from which the BB_k and BB_{k_j} are defined. The Developing Working Structure technique assisted in the selection of working structures that better reflect the physical effect needed for the formulated FRs (Pahl, 2007). The representation of BB_k is presented in Table 4.

Table 4. FLP building blocks.

DMs	*Building blocks (BBk)*		*Functional Requirement Class (FRk)*			*Design Parameter Class (DPk)*	
DM1:	SP Infeed		FR1.3: Orientate SP			DP1.3: SP Turner	
			Turning angle [°]	Production rate [sp/h]	Sec. pkg. morphology	Actuators [-]	Turning length [mm]
	BB1.1	SP turner	FR1.3.1	FR1.3.2	FR1.3.3	DP1.3.1	DP1.3.2
	BB1.1.1:	Dual lane turner	0, 90, 180, 270	> 1200,0	R&R, F&R	2	> 1600,0
	BB1.1.2:	Bump turner	0, 90	< 1200,0	R&R	2	> 1000,0
	BB1.1.3:	Pop-up turner	0, 90, 180, 270	< 900,0	R&R, R&I, F&R, F&I	3	> 800,00
DM3:	PLT dispenser		FR2.1: Buffer PLTs				
			Autonomy [h]	Production rate [sp/h]			
	BB3.1	PLTs magazine	FR2.1.1	FR2.1.2			
	BB3.1.1:	< 10,0 [plt]	> 1,0	< 600,0			
	BB3.1.2:	< 15,0 [plt]	> 1,0	< 900,0			
DM5:	Row builder		FR3.1: Build row			DP3.1: Row builder	
			Production rate [sp/h]	Footprint [m^2]		Actuators [-]	Drive pwr. [kW]
	BB5.1	Row builder	FR3.1.1	FR3.1.2		DP3.1.1	DP3.1.2
	BB5.1.1:	Internal	< 600,0	< 2,0		2	> 2,0
	BB5.1.2:	External	< 900,0	< 4,0		3	< 2,0
			FR3.2: Move row to layer position			DP3.2: Row elevator	
			Load height [mm]	Production rate [sp/h]		Application [-]	
	BB5.2	Row elevator	FR3.2.1	FR3.2.2		DP3.2.1	
	BB5.2.1:	H < 1520,0 [mm]	< 1520,0	> 600,0		Standard	
	BB5.2.2:	H < 1950,0 [mm]	< 1950,0	< 600,0		Standard	
	BB5.2.3:	H < 2200,0 [mm]	< 2200,0	< 500,0		Special	
DM6:	Layer builder		FR3.4: Move layer to load height			DP3.4: Layer elevator	
			Load height [mm]	Production rate [sp/h]		Application [-]	
	BB6.1	Layer elevator	FR3.4.1	FR3.4.2		DP3.4.1	
	BB6.1.1:	H < 1520,0 [mm]	< 1520,0	> 600,0		Standard	
	BB6.1.2:	H < 1950,0 [mm]	< 1950,0	< 600,0		Standard	
	BB6.1.3:	H < 2200,0 [mm]	< 2200,0	< 500,0		Special	
			FR3.6: Place layer onto pallet/load			DP3.4: Layer elevator	
			Layer weight [kgf]			Application [-]	Drive pwr. [kW]
	BB6.2	Layer elevator	FR3.6.1			DP3.4.2	DP3.4.3
	BB6.2.1:	M < 150,0 [kgf]	< 150,0			Standard	< 3,0
	BB6.2.2:	M < 300,0 [kgf]	< 300,0			Special	> 5,0
DM8:	Load conveyor		FR4.2: Discharge load			DP4.2: Load outfeed conveyor	
			Load weight [kgf]	Discharge type [-]		Track height [mm]	
	BB8.1	Load conveyor	FR4.2.1	FR4.2.2		DP4.2.1	
	BB8.1.1:	Pallet Jack	< 2000,0	Man. / Ass.		200,0	
	BB8.1.2:	AGV	< 2000,0	Automatic		400,0	
DM9:	Stretch wrapping		FR5.2: Pre-stretch the film			DP5.2: Film pre-stretch unit	
			Stretch ratio [%]			Actuators [-]	Transmission [-]
	BB9.1	Pre-stretch unit	FR5.2.1			DP5.2.1	DP5.2.2
	BB9.1.1:	FT < 95,0 [%]	< 95,0			1	Fixed
	BB9.1.2:	FT < 150,0 [%]	< 150,0			1	Fixed
	BB9.1.3:	FT < 300,0 [%]	< 300,0			1	Fixed
	BB9.1.4:	VT < 400,0 [%]	< 400,0			2	Variable
			FR5.3: Wrap the film on the load perimeter			DP5.3: Load turntable	
			Load weight [kgf]	Discharge type [-]		Plate style [-]	Transmission [-]
	BB9.2	Load turntable	FR5.3.1	FR5.3.2		DP5.3.1	DP5.3.2
	BB9.2.1:	Pallet Jack	< 1200,0	Manual		W	Friction
	BB9.2.2:	Fork Lift	< 2000,0	Assisted		O	Roller chain
	BB9.2.3:	Roller Conveyor	< 2000,0	Automatic		O	Roller chain
			FR5.4: Wrap the film along the load height			DP5.4: Spool carriage	
			Load height [mm]	Production rate [sp/h]		Application [-]	
	BB9.3	Spool carriage	FR5.4.1	FR5.4.2		DP5.4.1	
	BB9.3.1:	H < 1520,0 [mm]	< 1520,0	> 600,0		Standard	
	BB9.3.2:	H < 1950,0 [mm]	< 1950,0	< 600,0		Standard	
	BB9.3.3:	H < 2200,0 [mm]	< 2200,0	< 500,0		Special	
DM10:	DS dispenser		FR6.3: Move DS to load height			DP6.4: DS elevator	
			Load height [mm]	Production rate [sp/h]		Application [-]	
	BB10.1	DS elevator	FR6.3.1	FR6.3.2		DP6.4.1	
	BB10.1.1:	H < 1520,0 [mm]	< 1520,0	> 600,0		Standard	
	BB10.1.2:	H < 1950,0 [mm]	< 1950,0	< 600,0		Standard	
	BB10.1.3:	H < 2200,0 [mm]	< 2200,0	< 500,0		Special	
DM11:	Frame		FR3.4: Move layer to load height			DP7.1: Safety guarding	
			Load height [mm]	Production rate [sp/h]		Application [-]	
	BB11.1	Frame	FR3.4.3	FR3.4.4		DP7.1.1	
	BB11.1.1:	H < 1520,0 [mm]	< 1520,0	> 600,0		Standard	
	BB11.1.2:	H < 1950,0 [mm]	< 1950,0	< 600,0		Standard	
	BB11.1.3:	H < 2200,0 [mm]	< 2200,0	< 500,0		Special	

3.3 Physical Modeling Through Economic Evaluation of Physical Modules

Based on the formulated solution principles and existing process capabilities, the DPs were instantiated as physical components and assemblies for each DM identified in Table 3. The economic evaluation was performed only for those PMs derived from the BB_{k_j} presented in Table 4. The performance appraisal followed the Utility Analysis proposed by Yoshimura and Takeuchi (1994). The AHP was additionally employed to determine the relative importance of each functional attribute considered in the composite utility calculation. The cost estimation was performed according to the Pragmatic Approach to Product Costing developed by Tseng and Jiao (1997a). The cost-related design features considered in the FLP costing were: (i) number of motions, (ii) enclosure area, (iii) number of safety doors and (iv) number of light curtains. Table 5 listed the physical modules candidates and its respective measurements of utility (U) and relative cost (C).

Table 5. Physical modules U-C analysis.

Physical Modules Candidates (PMs)		*U*	*C*
PM1-1:	SP Infeed - Dual lane	0,85	0,80
PM1-2:	SP Infeed - Bump turner	0,39	0,80
PM1-3:	SP Infeed - Pop-up	0,94	1,00
PM3-1:	PLT dispenser < 10,0 [plt]	0,60	0,85
PM3-2:	PLT dispenser < 15,0 [plt]	0,90	1,00
PM4-1:	Base - Pallet jack	0,89	0,17
PM4-2:	Base - Turntable "W" plate	0,62	0,58
PM4-3:	Base - Turntable "O" plate	0,81	0,58
PM4-4:	Base - Turntable roller conveyor	1,00	1,00
PM5-1:	Row builder - Internal	0,63	0,28
PM5-2:	Row builder - External H < 1520,0 [mm]	0,85	0,88
PM5-3:	Row builder - External H < 1950,0 [mm]	0,85	0,95
PM5-4:	Row builder - External H < 2200,0 [mm]	0,85	1,00
PM9-1:	Stretch wrapping FT < 95,0 [%] H < 1520,0 [mm]	0,24	0,78
PM9-2:	Stretch wrapping FT < 95,0 [%] H < 1950,0 [mm]	0,24	0,82
PM9-3:	Stretch wrapping FT < 95,0 [%] H < 2200,0 [mm]	0,24	0,85
PM9-4:	Stretch wrapping FT < 150,0 [%] H < 1520,0 [mm]	0,38	0,78
PM9-5:	Stretch wrapping FT < 150,0 [%] H < 1950,0 [mm]	0,38	0,82
PM9-6:	Stretch wrapping FT < 150,0 [%] H < 2200,0 [mm]	0,38	0,85
PM9-7:	Stretch wrapping FT < 300,0 [%] H < 1520,0 [mm]	0,75	0,78
PM9-8:	Stretch wrapping FT < 300,0 [%] H < 1950,0 [mm]	0,75	0,82
PM9-9:	Stretch wrapping FT < 300,0 [%] H < 2200,0 [mm]	0,75	0,85
PM9-10:	Stretch wrapping VT < 400,0 [%] H < 1520,0 [mm]	1,00	0,93
PM9-11:	Stretch wrapping VT < 400,0 [%] H < 1950,0 [mm]	1,00	0,97
PM9-12:	Stretch wrapping VT < 400,0 [%] H < 2200,0 [mm]	1,00	1,00
PM11-1:	Frame M < 150,0 [kgf] H < 1520,0 [mm]	1,00	0,72
PM11-2:	Frame M < 150,0 [kgf] H < 1950,0 [mm]	1,00	0,76
PM11-3:	Frame M < 150,0 [kgf] H < 2200,0 [mm]	1,00	0,79
PM11-4:	Frame M < 300,0 [kgf] H < 1520,0 [mm]	1,00	0,93
PM11-5:	Frame M < 300,0 [kgf] H < 1950,0 [mm]	1,00	0,97
PM11-6:	Frame M < 300,0 [kgf] H < 2200,0 [mm]	1,00	1,00

Fig. 10 presents the results of the economic evaluation, from which different PMs were selected for various design strategies in the product family design. As shown in Fig. 10(a) and 10(c), those PMs which dropped in the non-preferable region were discarded from product family design. In Fig. 10(b), although the PM4-2 has not fallen in a non-preferable area, it was discarded based on the difficulty to fit it on the FLP platform.

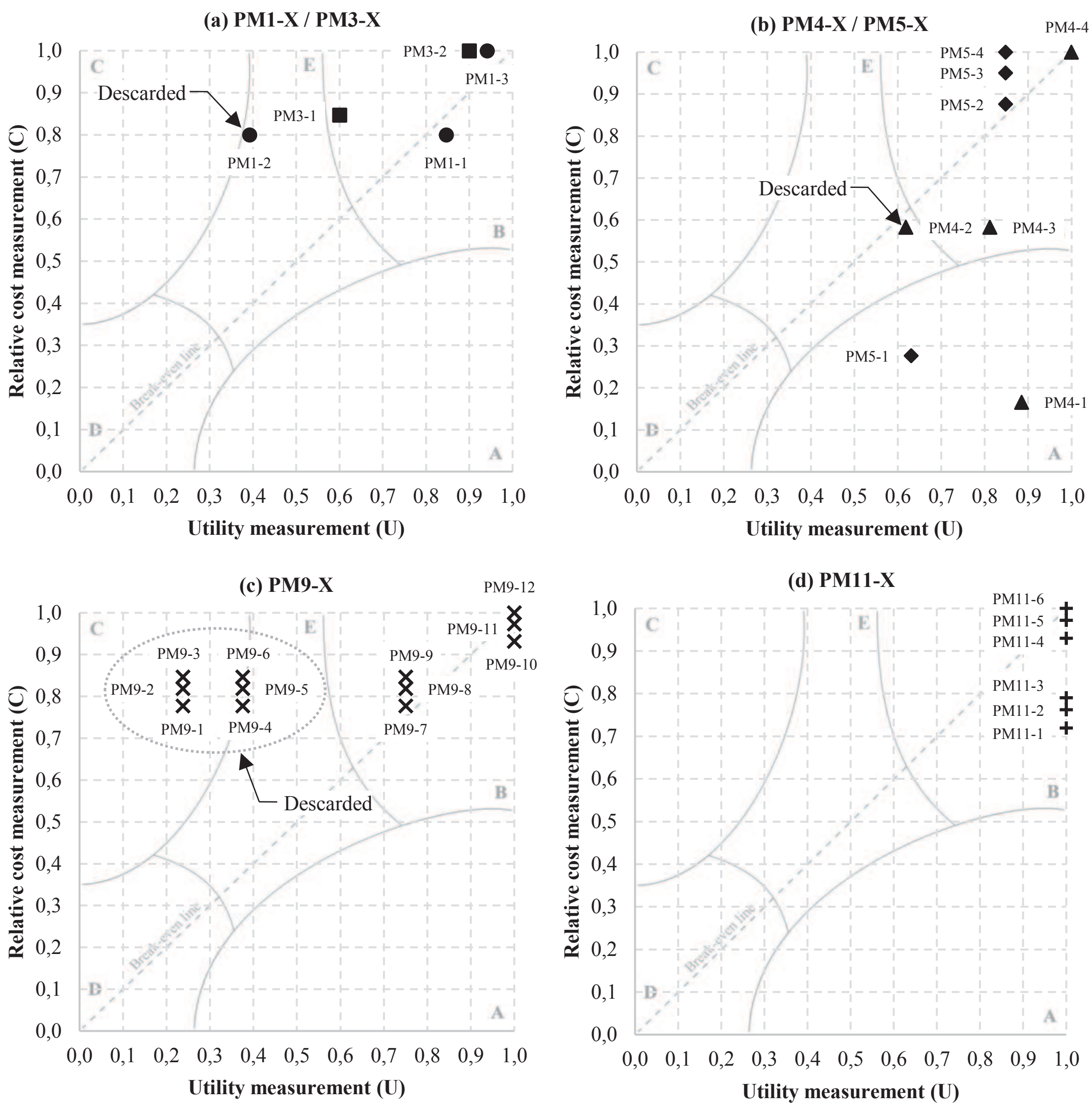


Fig. 10. **(a)** SP infeed / PLT dispenser; **(b)** base / row builder; **(c)** stretch wrapping; **(d)** frame.

With reference to the modular structure in the technical view, the configuration structure of product family design is established concerning PMs. Table 6 presents a simplified configuration structure for FLPPF given in a tabular form.

Table 6. Configuration structure for an FLPPF.

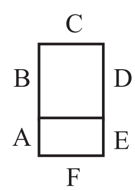
	Assy. level 1 2 3 4 5 6	*Description*	*Qty.*
-	PM1-1:	SP Infeed - Dual lane	1,0
-	A1-1.1:	SP brake conveyor	1,0
-	C1-1.1.1:	Gearmotor	1,0
-	C1-1.1.2:	Rubber top modular belt	1,0
-	C1-1.1.3:	Sprockets	10,0
-	C1-1.1.4:	Shafts	2,0
-	C1-1.1.5:	Bearings	2,0
-	C1-1.1.6:	Structure	1,0
+	A1-1.2:	SP singulation conveyor	1,0
+	A1-1.3:	SP dual lane turner	1,0
+	PM1-3:	SP Infeed - Pop-up	1,0
+	PM2:	SP barcode reader	1,0
+	PM3-1:	PLT dispenser < 10,0 [plt]	1,0
+	PM3-2:	PLT dispenser < 15,0 [plt]	1,0
+	PM4-1:	Base - Pallet jack	1,0
+	PM4-3:	Base - Turntable "O" plate	1,0
+	PM4-4:	Base - Turntable roller conveyor	1,0
+	PM5-1:	Row builder - Internal	1,0
+	PM5-2:	Row builder - External H < 1520,0 [mm]	1,0
+	PM5-3:	Row builder - External H < 1950,0 [mm]	1,0
+	PM5-4:	Row builder - External H < 2200,0 [mm]	1,0
+	PM6:	Layer builder	1,0
+	PM7:	Load labeling	1,0
+	PM8:	Load conveyor	1,0
+	PM9-7:	Stretch wrapping FT < 300,0 [%] H < 1520,0 [mm]	1,0
+	PM9-8:	Stretch wrapping FT < 300,0 [%] H < 1950,0 [mm]	1,0
+	PM9-9:	Stretch wrapping FT < 300,0 [%] H < 2200,0 [mm]	1,0
+	PM9-10:	Stretch wrapping VT < 400,0 [%] H < 1520,0 [mm]	1,0
+	PM9-11:	Stretch wrapping VT < 400,0 [%] H < 1950,0 [mm]	1,0
+	PM9-12:	Stretch wrapping VT < 400,0 [%] H < 2200,0 [mm]	1,0
+	PM10-1:	DS dispenser H < 1520,0 [mm]	1,0
+	PM10-2:	DS dispenser H < 1950,0 [mm]	1,0
+	PM10-3:	DS dispenser H < 2200,0 [mm]	1,0
+	PM11-1:	Frame M < 150,0 [kgf] H < 1520,0 [mm]	1,0
+	PM11-2:	Frame M < 150,0 [kgf] H < 1950,0 [mm]	1,0
+	PM11-3:	Frame M < 150,0 [kgf] H < 2200,0 [mm]	1,0
+	PM11-4:	Frame M < 300,0 [kgf] H < 1520,0 [mm]	1,0
+	PM11-5:	Frame M < 300,0 [kgf] H < 1950,0 [mm]	1,0
+	PM11-6:	Frame M < 300,0 [kgf] H < 2200,0 [mm]	1,0

In practical production environments, a product code system is usually employed to identify different parts, assemblies, and product variants. Table 7 shows the method adopted for coding the FLPPF. Fig. 11 illustrates the conceptual design of some FLP product variants.

Table 7. Product code system for an FLPPF.

Product code = **AAA.BBB.CCC.DDD.EE-X.FF.GG-X.HH.I.JJ.KK-X.LLL-X.MM-X**

AAA =	**Family designator**
FLP =	Floor level palletizer
BBB =	**Production rate**
600 =	600 [sp/h]
900 =	900 [sp/h]
CCC =	**Load height**
152 =	< 1520,0 [mm]
195 =	< 1950,0 [mm]
220 =	< 2200,0 [mm]
DDD =	**Layer weight**
150 =	150,0 [kgf]
300 =	300,0 [kgf]
EE-X =	**SP infeed**
DL =	Dual lane
PP =	Pop-up
FF =	**Bar code reader**
0 =	None
BC =	Bar code reader
GG-X =	**Pallet dispenser**
0 =	None
10 =	< 10,0 [plt]
15 =	< 15,0 [plt]
HH =	**Base**
PJ =	Standard pallet jack
TO =	Turntable "O" plate
TR =	Turntable roller conveyor
I =	**Row builder**
I =	Internal
E =	External
JJ =	**Load labeling**
0 =	None
LB =	Load labeling
KK-X =	**Load conveyor**
0 =	None
LC =	Load conveyor
LLL-X =	**Stretch wrapping**
0 =	None
300 =	FT < 300,0 [%]
400 =	VT < 400,0
MM-X =	**DS dispenser**
0 =	None
DS =	DS dispenser
X =	**Direction**



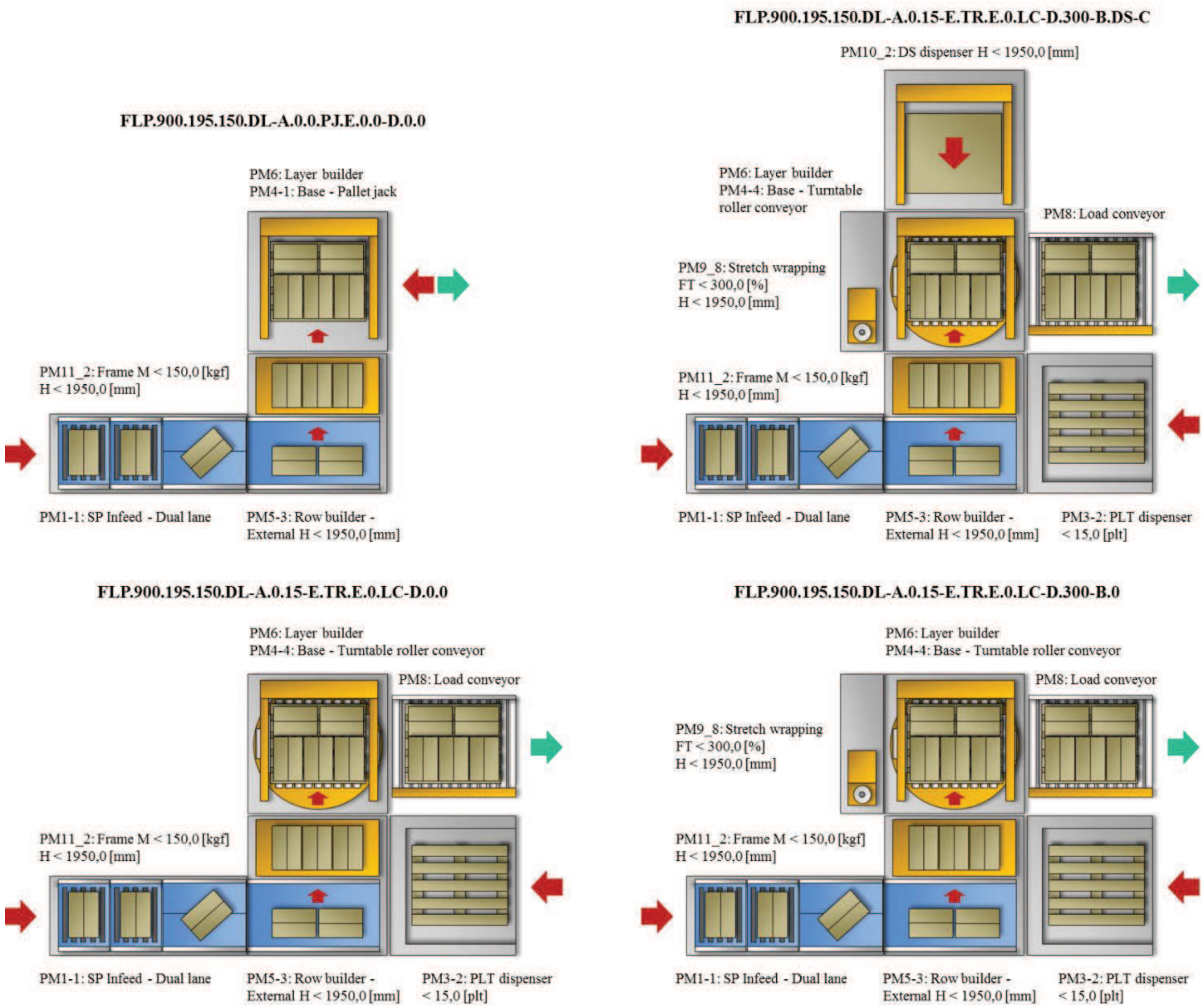


Fig.11. Examples of FLP product variants.

4. CONCLUSION

This article presented the application of the PFA methodology in the development of an FLPPF with the purpose of elucidating the implementation of MC strategy in a CGI company from a product development perspective. The development of the FLPPF addressed in this paper went through the three following views of PFA methodology: (i) functional view, (ii) technical view and (iii) physical view. The result of such application was a conceptual design of the proposed product family. Based on the practical implementation of the theory, this particular case identified some opportunities for improvements along the development process.

In the functional view, the method suggests the analysis of existing product portfolio in conjunction with the domain knowledge to determine the FRs. It is fundamental, however, the design of industrial machinery, such as FLPs, deeply depends on the functional requirements derived from the process which these machines aim to automate. For that reason, an additional technique, named Function Structures Establishment (Pahl, 2007), was employed to break down the palletizing process into sub-functions as a way to complement the formulation of the FRs. In this application, considering the number of FRs to be prioritized against a multi-criteria AHP matrix, the number of pairwise comparisons would overcome 4.000 combinations. With the purpose of reducing it, the AHP was employed to weight the customer needs, then the House of Quality matrix was used to transfer the priorities of the customer needs into FRs. (Nakui, 1987). Even FCM being a powerful tool to determine the FRs clusters, additional descriptive statistics techniques, such as confidence interval, was adopted here to define the limits between adjacent clusters, facilitating in this way the establishment of the FRs targets and its limits (Krishnamoorthi, 2011).

In technical view, specifically in a modular structure definition, the working principle of a solution technology is of particular concern in determining how to fit DMs into the structure. To assist in the selection of working principles and structures, this paper used a supplementary technique termed Developing Working Structure (Pahl, 2007). In this section, it was also noticed that interactions specification derived not only from their inter-cell elements in a decomposed design matrix but also through the arrangement of DMs into an FLP preliminary layout.

In physical view, the determination of CAs, for each DM identified in the technical view, was also assisted by the Developing Working Structure technique (Pahl, 2007). In the economic evaluation, the AHP was additionally employed to determine the relative importance of each functional attribute considered in the composite utility calculation.

Based on the empirical results presented in this study, although there exist some opportunities for improvements, it is reasonable to attest the feasibility of PFA methodology as a framework for conceptually design complex industrial machinery, such as FLPs. It was also noticed the significant impacts the PFA can pose on the production strategy of CGI companies, which are primarily engineering to order (ETO) and could have its operations shifted to make to order (MTO) or assembly to order (ATO) approach. Besides that, another topic that needs to be more investigated is the potential of PFA in providing physical flexibility for industrial machinery to support the software revolution imposed by Industry 4.0.

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