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Methodical Design of a Physical Internet Compatible Pallet System

MASTER'S THESIS

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Affidavit

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Acknowledgments/Forewords

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Abstract

How goods are transported today within the global supply chain is neither ecologically, economically nor socially sustainable. The growing importance of sustainability and environmental protection in today's world makes it necessary to establish new concepts and approaches in the logistics and transport sector. Physical Internet offers an innovative approach for efficiency optimization and thus increasing sustainability in the field of global transport of goods.

The long-term concept and the requirement for fundamental structural changes in the global supply network for the planned implementation of PI technology still result in little attention for this innovative strategy in the traditional logistics and transport sector.

This paper is concerned with the question of how innovative PI approaches can be efficiently and sensibly combined with the situation and application scenarios in the current transport sector to make the complex PI philosophy accessible to a broad mass of users and to enable a long-term implementation of the PI technology.

The logistic element pallet is at the centre of this analysis. Technology transfer from earlier PI projects and a detailed requirements analysis form the basis for a methodical design process of a PI compatible pallet system, which allows PI technology to be linked with applications in traditional transportation and thus increase the reputation and acceptance of the PI philosophy in this sector.

Kurzfassung

Moderne Gütertransport ist in der derzeitigen Form weder okölogisch noch ökonomisch nachhaltig. Die wachsende Bedeutung der Begriffe Nachhaltigkeit und Umweltschutz erfordern die Entwicklung von neuen, innovativen Ansätzen und Konzepten zur Effizienzsteigerung und damit Steigerung der Nachhaltigkeit im Bereich der globalen Logistik und Transportbranche.

Physical Internet bietet einen innovativen Ansatz für die Effizienzsteigerung im Bereich des globalen Warentransportes

Die Notwendigkeit grundlegendender struktureller Veränderungen und Reformationen im Transport und Logistikwesen, die eine durchgängige PI Implementierung voraussetzt, führen zu wenig Akzeptanz und Anerkennung dieses innovativen Ansatzes in der Logistik.

Die Vorliegende Arbeit beschäftigt sich damit wie die Ansätze aus PI effizient und sinnvoll mit Anwendungen aus dem modernen Logistikbereich kombiniert werden können, um einer breiten Masse an potentiellen Usern die Technologien von PI zugänglich machen zu können. Dabei steht die Untersuchung von Paletten im Mittelpunkt. Durch Technologie Transfer und ein methodischer Entwicklungsprozess erlauben die konzeptionelle Entwicklung einer PI Palette, die die Philosophie von PI langfristig im Transport und Logistiksektor etablieren kann.

Table of Contents

1 Introduction

This chapter clarifies the purpose of this thesis and defines the research questions, which are answered within this handheld document.

1.1 Motivation

As the term Physical Internet (PI) is more frequently used in recent years, it seems to gain more importance in the field of transportation and logistics. The author's motivation for being an active part of this innovative movement and joining the PI community became evident based on his interests in the field of new technologies and innovative ideas as well as their way from a concept to their full implementation through the different stages of the industry.

According to that, the fundamental goal of this thesis is to figure out the possibilities and tools used for introducing PI into the logistics section of the industry.

As the logistics branch is fairly established, compared to the newly introduced concept of PI, this thesis shall further focus on combining elements of traditional logistics with ideas of the PI philosophy in order to be efficient at introducing PI to the transport and logistics sector until 2050.

Referring to these respective aspects, the author decided to put pallets into the focus of research and develop a way to use pallets as a tool for PI implementation.

1.2 Research Questions

One of the long-term goals of PI indicates that transports and handling of goods shall be fully based on PI Containers by 2050 which means that pallets in their current form may lose their purpose in that future scenario. [MMB10, p8]

This thesis addresses two main questions to find possible applications for pallets in PI. The focus on possible usage of pallets compatible with Physical Internet will set on last-mile and first-mile deliveries as well as handling operations at manufacturer's and end consumer's warehouses.

In accordance with these goals, this thesis will focus on the following research questions.

- How can the knowledge and technology of PI be transferred to the standard logistic element pallet in order to create a PI compatible tool and find scenarios within last-mile and first-mile delivery in the PI Transportation Network, with the goal of the introduction the PI philosophy to a broad mass of potential users?
- Which benefits can PI compatible pallets bring to manufacturers and consumers and in which fields of the transportation and logistics branch lies the potential of PI Pallets?

1.3 Structure of the Thesis

This thesis is divided into two main parts, the theoretical part, and the methodical part.
The theoretical part gives an overview of the current situation in the transport and logistics branch, including the usage of pallets, as well as theoretical background of PI and PI Transportation Network, last mile, first-mile delivery, and PI Containers in particular. This section also includes the description and the theoretical background of methods and tools used in this thesis.
The methodical part contains the executed methodical development process of a PI suitable pallet system.
This thesis concludes with a summary of the outcomes and solutions as well as a short outlook about the potential and further steps.
In figure 1, the basic structure is shown, including the two central sections as well as their subdivision.

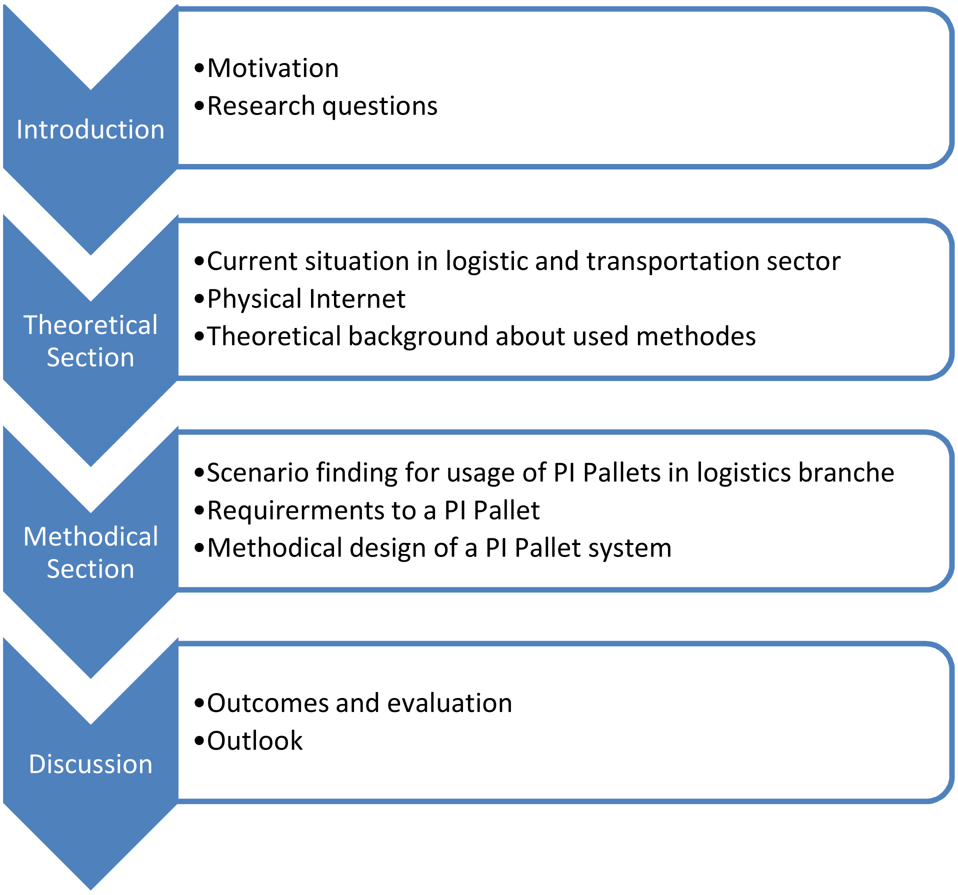


figure 1: structure of this thesis

2 Theoretical Background

This chapter introduces the relevant background information as well as a technical insight into pallet systems. In addition, it offers a general idea of PI and trends, goals and realization concepts concerning PI.

2.1 Pallets in the Logistics and Transport Sector

Pallets and transport of goods, these two phrases seem to be inseparably connected for a long time. In almost every sector of the industry, pallets are used as a load carrier, which proves their immense importance within the whole logistics and transportation sector. Compared to that, pallets seem to receive little attention within our minds because they seem to be obvious to all of us. However, changing conditions in the industry (e.g. increasing automated processes) results in a change of requirements and needs for pallets and load carriers. The widespread EURO Pallet is no longer the dominant pallet system on the market. Different scenarios and applications nowadays require different pallets concerning material, shape and boundary conditions. [MMS06, p15]
This chapter shows the most relevant design concepts for pallets as well as their threats, strengths and field of application and highlights how multifaceted the pallets are used in the sector of logistics at this current state of technology.

2.1.1 Pallet Systems Used in the Current Logistics Branch

According to related statistics, an estimated amount of 1 billion pallets is in circulation all over the world. Europa holds the biggest share of about 50% of all worldwide circulating pallets. [HK15, p19]
However, because of various aspects, not every pallet is suitable for every situation and sector in the logistics and transport industry. This requires a pool of differently shaped and designed pallets to meet the requirements for the manifold tasks in logistics.

2.1.2 Pallet Variants in Circulation

Nowadays, state of the art pallets differ from one another, mainly in material and design. The most important variants of pallets concerning their material and design are listed and described in the following.

2.1.2.1 Material

To simplify the explanation, only the following main groups of pallet materials will be explained: solid wood, pressed wood, plastic, metal and corrugated paper
Subgroups of materials, as well as special materials, have not been taken into consideration.

Solid Wood:
Most pallets in use are made of solid wood (including EURO pallets)
Pallets of solid wood can be characterized by the following advantages and disadvantages [MMS06, p47ff]:

Advantages:
- High load capacity
- High robustness
- High durability
- Low price

Disadvantages:
- High deadweight
- High levels of moisture absorption
- Potential safety risk due to used nails and splintering
- Risk of vermin infestation

figure 2: EPAL CP5 Pallet made of Wood [EPA19]

Pressed Wood:
Pallets made of pressed wood can be characterized by the following advantages and disadvantages [MMS16, p52ff]:

Advantages:
- Low deadweight
- Biodegradable

Disadvantages:
- High risk of mechanical damage
- High level of moisture absorption
- Potential safety risk due to used nails and splintering
- Risk of vermin infestation

figure 3: INKA Pallet Typ F8-5 [INK19]

Plastic:
Pallets made of plastic can be characterized by the following advantages and disadvantages [MMS06, p54ff]:

Advantages:
- Very high durability
- Resisting humidity and chemicals
- Recyclable
- No splintering

Disadvantages:
- High price
- High deadweight

figure 4: Capka hygienic plastic pallets [CAP19]

Metal:
For this categorization, pallets of different metals (e.g. aluminium or steel) will not be characterized individually but depicted as one group.
Pallets made of metal can be characterized by the following advantages and disadvantages [MMS06, p59ff]:

Advantages:
- Very high durability
- High load capacity

Disadvantages:
- High deadweight

figure 5: LKE aluminium pallet [LKE19]

Corrugated Paper:
Pallets made of corrugated paper can be characterized by the following advantages and disadvantages [MMS06, p64ff]:

Advantages:
- low deadweight
- biodegradable

Disadvantages:
- not resistant against environmental conditions (e.g. humidity)
- low durability

figure 6: Pallet made of corrugated paper [SK19]

2.1.2.2 Design

Besides the differences in material, pallets can be distinguished by design and structure. The main design distinction concerning handleability and operability, besides others, is the difference between two-way and four-way design.

Two-way Pallet:
Two-way pallets are pallets which can be operated and handled from two directions. In the case of this design, all other sides of the pallet are closed or have no opening for forklift insertion. [HPE17, p59]
According to this definition, two-way pallets can be shaped differently. Figure 7 exemplarily shows a specific design of a two-way pallet.

figure 7: two-way pallet [UK19]

Four-way Pallet
Compared to two-way pallets, four-way pallets can be handled and operated by standard handling equipment from all four sides. This feature does lead to a lack of stability compared to the appropriate design of a two-way pallet. [HPE17, p61]
Figure 8 exemplarily shows the design of the most frequently used four-way pallet, the EURO Pallet.

figure 8: EPAL EURO Pallet (EPAL1) [EPA19]

2.1.3 Deployment Scenarios of Existing Pallet Systems

This chapter clarifies the deployment scenarios within the transport and logistics sector, where pallet systems are currently used in. This clarification addresses the difference between single-use pallet systems and multi-use pallet systems as well as the theoretical background of pallet pooling.

Single-Use Pallets:
Single-use pallets are designed for a scenario including the sender's waiver of return of sent pallets. This indicates that the pallet is designed for a single one-way transportation process. Further, single-use pallets are often not normed or standardized, which enables the customization of the pallet for every individual good which needs to be transported. Based on that, one-way pallets can be made of almost every material (see chapter 2.1.2.1) and have many different shapes (see chapter 2.1.2.2). [MMS06, p43]
Figure 9 shows discarded single-use pallets made of wood.

figure 9: discarded single-use pallets [ALB19]

Multi-Use Pallets:

Compared to the pallet systems described previously, multi-use pallets are designed to be exchanged, returned and resold between senders and receivers. This indicates a stable and robust design, necessary to fulfil multiple transport and handling processes during the lifespan of a pallet, as well as the usage of standardized pallet systems. [MMS06, p43]

In order to give a short overview of transportation loops of multi-use pallets within good delivery, two different circuit concepts are described in the following, the approach of pallet exchange and the approach of pallet pooling.

Pallet Exchange:

The pallet exchange approach defines a relation between a sender, a receiver and a logistics provider (haulier), which forms a closed loop. Palletized goods are transported by the logistics provider from the sender to the receiver and an appropriate number of empty pallets is delivered back from the receiver to the sender. This system results in a permanent exchange of pallets between senders and receivers. [MTM19]

Figure 10 shows the principle of a closed transportation loop according to the pallet transportation within a pallet exchange system.

figure 10: principle of pallet exchange [MTM19]

The system of pallet exchange shows the following weaknesses [MMS06, p35]:

- Decreasing quality of pallets through their lifespan
- Occurring damages of the pallets
- High administrative and documentation efforts
- High storage effort for pallets at sender and receiver
- Undefined property throughout the whole transportation loop

Pallet Pooling:
Compared to the system of pallet exchange, the system of pallet pooling aims to expand the loop by inserting a fourth party, a pallet leasing company. This increases transportation efforts and the storing and handling effort at the pallet leasing company. On the other hand, this system also shows the decrease in storing effort at senders' and receivers' warehouses as well as efficient usage of different pallet types. [YHD14]
Figure 11 shows the principle of a closed transportation loop based on pallet transportation within a pallet pooling system. [YHD14]

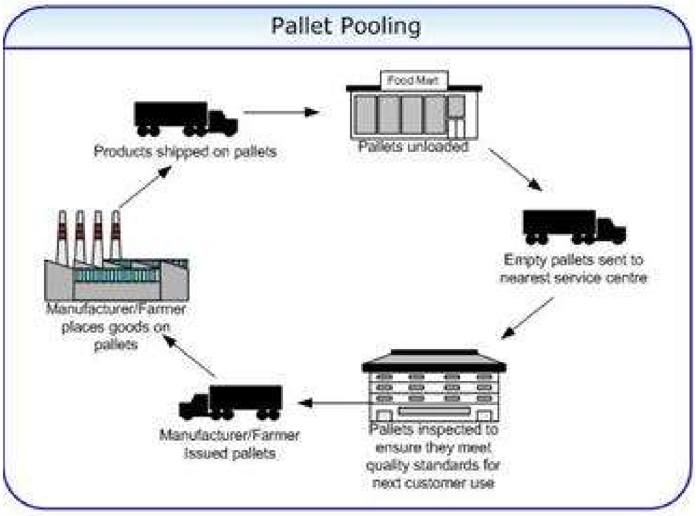


figure 11: principle of pallet pooling [YHD14]

Compared to pallet exchange systems, pallet pooling can be characterized by the following aspects [YHD14]:

- Low purchasing and storing effort at sender and receiver
- High-quality pallets
- Little loss of pallets
- Clear definition of property through the whole process

2.2 Physical Internet

As described in the previous chapter, the logistics sector and pallets have a long-shared history. Going into the future this common path might soon come to an end, as one goal of PI is to get rid of pallets in the logistics and transport sector.
This chapter investigates the basic philosophy of PI, as well as its goals and the growing importance of PI in logistics over the last few years. This allows the reader to have an insight into this innovative strategy which is necessary to understand the forecasts and predictions made in this thesis.

2.2.1 Rising Economic and Ecological Thinking in the Logistics and Transport Branch

Managing logistics and transport processes continuously progresses in terms of complexity. Transport companies have been facing challenges over the last few years. A change in the customers' mind-set based on their buying behaviour, legal regulations, climate change policies and megatrends (e.g. digitalization, urbanization, etc.) are forcing the industry to change their point of view and find innovative approaches and solutions to fulfil the needs of customers and industry. Offering products for a larger area within shorter delivering time frames on the one hand and reducing harmful emissions within the transport sector on the other hand, seems impossible. [BMM14, p13]
Due to changing boundary conditions and customer needs over the last couple of years, the idea of Physical Internet (PI) came up in 2006. The central concept of PI is to shift knowledge from the digital internet to the physical world of logistics and transportation in order to create an open, shared and interconnected network. [BMM14, p14]

2.2.2 PI Transportation Network

Data packages on the digital internet are transferred and sent from a sender to a receiver by passing a network of hubs and routers. The PI transfers this principle to the physical world by creating a global transportation network of hubs, called PI Hubs in the following. Goods are transported on optimized routes according to the utilization of transporters and covered distances, from PI Hub to PI Hub within the transportation network. Compared to an appropriate, state of the art transport process, applying the PI approach to transport of goods within a transportation network consisting of PI Hubs shows opportunities as well as weaknesses. On the one hand, the transportation network requires more single transportations as well as more handling and dispatching effort within this PI Transportation Network.

On the other hand, the distribution of goods via PI Hubs within this PI Transportation Network enables an increase of efficiency of single transports because of optimized routes, high utilization levels and a low number of required empty runs, which directly lead to economic and ecological advantages. [MON11, p78ff]
Figure 12 exemplarily shows the topology of a PI Transportation Network.

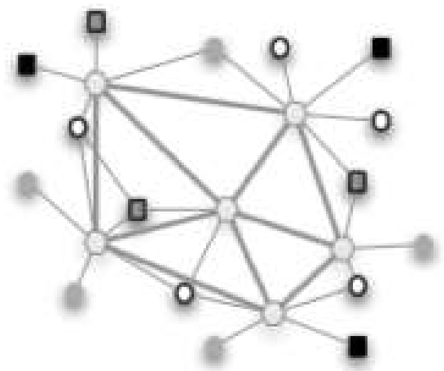


figure 12: topology of an interconnected PI Transportation Network

2.2.3 Encapsulating Goods and PI Containers

In order to be able to exploit the efficiency of the PI Transportation Network, goods need to be encapsulated. This allows an abstraction of the goods, regardless of their shape or form, like the process of forming data packages in the digital internet. In the physical world, this encapsulation is achieved by the introduction of PI Containers. PI Containers are available in different dimensions and are fully modular. This modularity allows forming load units out of single PI Containers. This flexible forming and reforming of load units out of different PI Containers is the key to gaining efficiency within the transportation network. Load units can be handled and transported as one unit from PI Hub to PI Hub where they are getting reformed according to the optimized distribution strategy. [MON11, p75ff]

2.2.4 MODULUSHCA

Within the MODULUSHCA (Modular Logistics Units in Shared Co-modal Net-works) project, 15 partners from research, logistics business, postal business and FMCG industry participated in close coordination with North American partners and the international PI Initiative, which represents the first contribution to the development of interconnected logistics in Europe. [LEJ15, p2]
One of the main outcomes of this project was the concept and methodical design of PI Containers, suitable for PI related tasks in order to fulfil the PI goal of encapsulating goods within the PI Transportation Network. [LEJ15, p2]

The main characteristics, created based on various requirements and needs from different points of view, were the modular dimensions as well as the interconnectivity between two or more PI Containers. [LEJ15, p8ff]
Figure 13 shows MODULUSHCA containers of different dimensions as well as the interconnectivity between two of them.

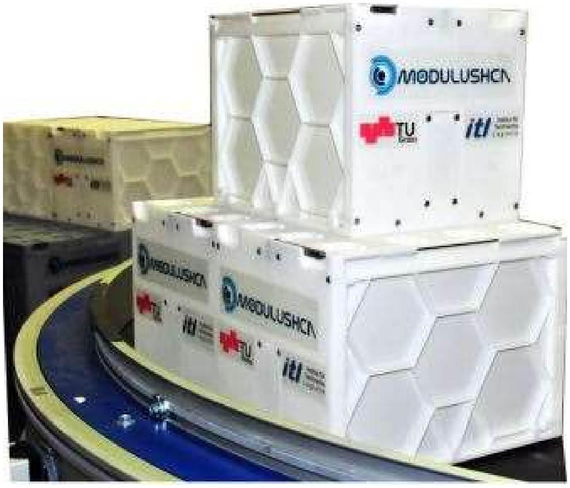


figure 13: MODULUSHCA container [LEJ15, p17]

2.3 Physical Internet Meets Traditional Logistics and Transport Logistics

In this chapter, typical scenarios within the traditional logistic branch, as well as potential scenarios within PI, are described. Further, commonalities and differences between PI and traditional transport of goods processes are carved out. This shall serve as a basis for a problem statement with regards to the compatibility of conventional logistics and PI. This problem statement will lead to the methodical part.

2.3.1 Palletizing Goods within Traditional Logistics

In traditional logistics, pallets of different shapes are widespread as load carriers because of their compatibility with most goods, regardless of their packaging and shape. [HPE17, p24]
Figure 14 shows the usage of pallets as a load carrier for flexible goods (left) as well as for rigid goods (right)

figure 14: Palletized flexible goods [HOR19] and palletized rigid goods [RAJ19a]

To secure the goods during transportation and handling processes, VDI 3968 lists different variants of load securing as following [VDI 3968]:

- Strapping
- Stretching
- Shrinking

Figure 15 shows the load securing techniques of strapping (left), stretching (middle) and shrinking (right)

figure 15: load securing techniques of strapping [RAJ19b], stretching [RAJ19c], and shrinking [RAJ19d]

2.3.2 Load Units and their Handling within the PI

Compared to the palletized load batches within traditional logistics, goods must be encapsulated and packed in PI Containers to handle them within PI (see chapter 2.2.3). That enables the abstraction of shape and form of goods, which leads to standardized handling and transport processes.
The base for the transport processes within the PI Transportation Network are PI Load Units, which are formed of PI Containers, containing encapsulated goods.

The literature shows contrasting approaches to handling and transporting these PI Load Units within the PI Transportation Network. These concepts concern the approach of pallet-less transportation of PI Load Units on the one hand and the concept of using traditional pallets as a load carrier for the PI Load Units within PI Transportation Network on the other hand.
The concept of pallet-less transportation and handling processes indicates the usage of suitable handling and transportation devices that can handle the PI Load Units directly by getting connected to them. This method of handling the PI Load Units requires special handling and transport devices within the whole transportation chain. [MMB10, p8]
Figure 16 shows the principle of pallet-less handling of PI Load Units by using a special PI mover.

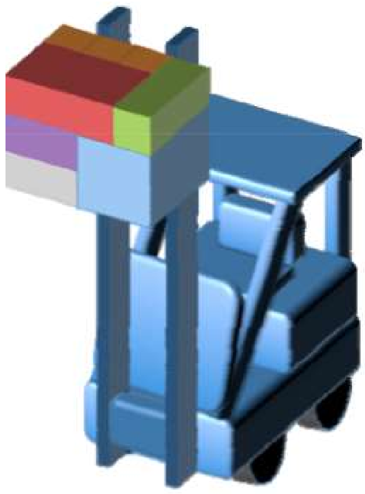


figure 16: Pallet-less handling of Load units by special PI mover [MMB10, p8]

As mentioned previously, other sources name the approach of using a pallet as a load carrier for transporting and handling PI Load Units within the PI Transportation Network. This approach includes the securing of the PI Load Units during transport and handling process on the pallet by one of the techniques listed in chapter 2.3.1 [CLU18, p33ff]
Figure 17 shows six palletized load units on standardized EURO Pallets.

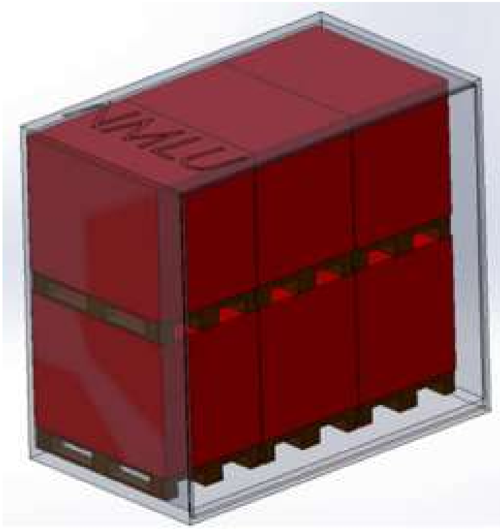


figure 17: palletized Load units on standardized EURO Pallets [FRA18, p33ff]

2.3.3 Problem Statement and Approach of PI Pallets

As described in chapter 2.3.2, there is no clearly defined way of transporting and handling processes of PI Load Units formed of encapsulated goods within a PI Transportation Network. There are two contradictory approaches based on the usage of pallets. Each of these approaches has a significant disadvantage:

- Pallet-less transportation does require the usage of special PI compatible handling and transportation devices. This may turn out to be an economic disadvantage for the senders and the receivers of goods, which would be forced to install such handling devices in order be to be part of the PI Transportation Network.
- The usage of pallets as load carriers does indicate the usage of a securing devices and material in order to lock the PI Load Unit to the pallet. Further, this means additional effort within the whole PI Transportation Network as well as negative ecological effects.

By transferring the idea and knowledge of interconnectivity between PI Containers (see chapter 2.2) to the element of a pallet, a PI compatible pallet would combine the advantages of both handling variants explained before to each other. PI Load Units formed of PI Containers could easily and fast be connected and disconnected to the PI compatible pallet, without the need of additional securing devices and material, which indicated the readiness of handling by forklifts at the sender and receiver as well as the pallet-less transportation and handling within the PI Transportation Network.
The relevant literature does not mention a PI compatible pallet system as an approach for handling and transporting PI Load Units within the PI Transportation Network.

3 Theoretical Background of Used Methods

This chapter contains the theoretical background of the methods used in this thesis. This includes the definitions and descriptions of single method steps and their connections to each other as well as the literary context. Therefore, these definitions and explanations are necessary to create traceability and transparency of the used methods in chapter 4.

3.1 Methodical Design Process

As the main task of this thesis is the methodical design of a product, namely a PI Pallet system, the used design methods will follow the guidelines of the established standards VDI 2221 "Methodik zum Entwickeln und Konstruieren technischer Systeme und Produkte" [VDI83], VDI 2222 "Konstruktionsmethodik - Methodisches Entwickeln von Lösungsprinzipien" [VDI97] and VDI 2223 "Methodisches Entwerfen technischer Produkte" [VDI04]. Figure 18 shows the design steps as well as the process steps, according to VDI 2221, which will be the basis for the methodical section of this thesis.

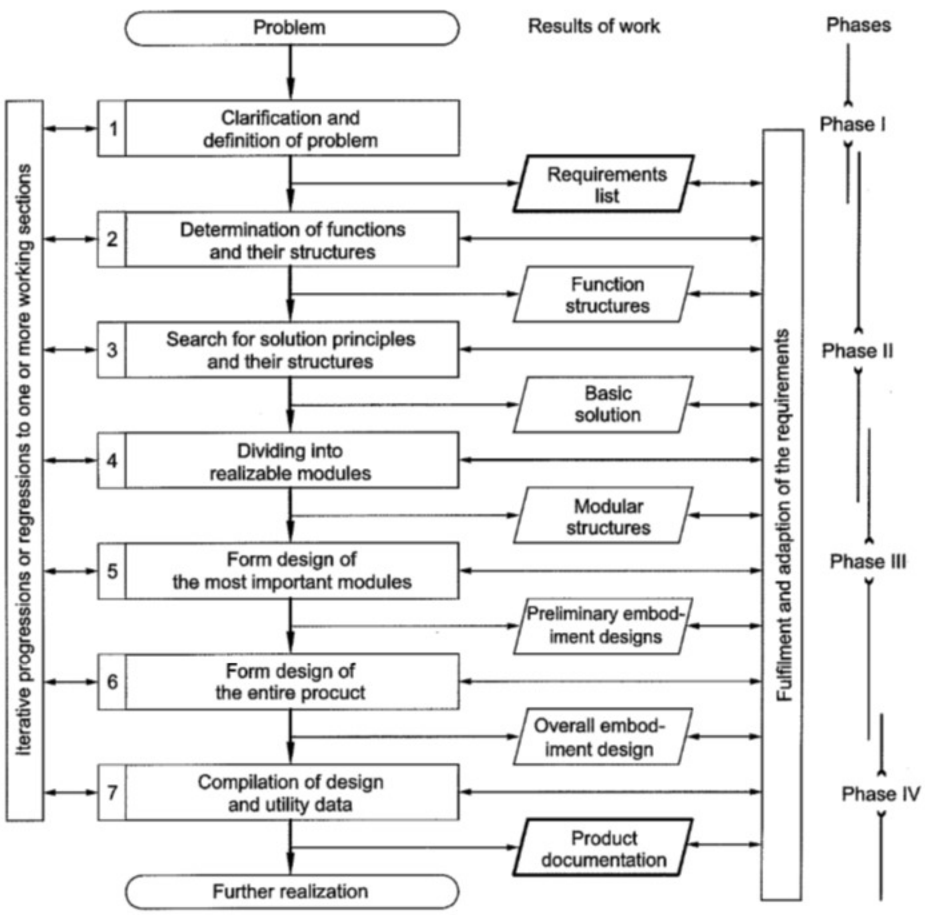


figure 18: methodical design steps according to VDI 2221 [VDI83, p9]

The single steps of the methodical design process, according to VDI 2221, shown and listed in figure 18, are described in detail in the following sub-chapters.

3.1.1 Problem Statement and Definition of User Scenarios

In 2.3.3, the problem, according to the current situation of logistics and transport branch combined with PI implementation, was outlined. This first step of the methodical design process includes the concretization and definition of this problem statement. To create a basis for the design of the end product, the outcome of this problem definition step can be used for creating the list of requirements, which is crucial for further design steps. [VDI83, p9f]
This statement will be expanded by user scenarios (see chapter 3.1.1.1) to further outline the basis for the design process.

3.1.1.1 User Scenarios

User scenarios are applied for finding potential use cases, where a potential costumer might use the product in future processes. That includes the description and explanation of the intended behaviour of the product as well as the user's behaviour during the usage and the interaction between the product and connected elements. [ING19]
In order to make these user scenarios understandable, the graphical standard notation EPC will be used, beside others, to figure out the sequences and processes of the user scenarios. This notation will be described in chapter 3.1.1.2.

3.1.1.2 Event Driven Process Chain (EPC)

EPC is a standardized graphical notation, which will be used in this thesis to illustrate the sequences and processes, define the user scenarios (see chapter 3.1.1.1) as well as the responsibilities and connections between the included elements. [AAL99, p2ff]
To have an overview of the notation, used elements are listed in the form of a legend for all flowcharts which contain EPC notation in figure 19.

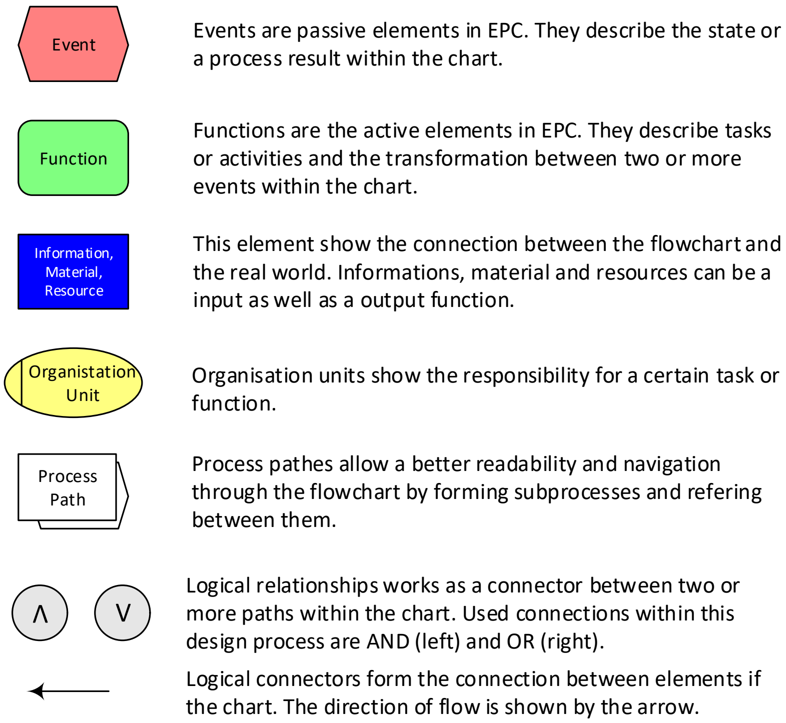


figure 19 Legend Event-Driven Process Chain (EPC) [AAL99, p2ff]

3.1.2 List of Requirements

The next step according to VDI 2221 [VDI83, p9f] is the definition of requirements for the final product. Numerous aspects can define requirements, user expectations and legal constraints are mentioned here exemplarily.
Requirements can occur in the form of explicit or implicit requirements. According to the definition, implicit requirements are evident, because they are defined by the basic function or are state of the art. They directly determine the success of the product on the market. In contrast, explicit requirements are formed by the user, designer or any other constraints. [FG13, p328ff]
Furthermore, the list of requirements can be divided into requirements which must be fulfilled by the final product in any case, called constraints, on the one hand and requirements which are not mandatorily necessary and need to be seen as a nice-to-have feature, called wishes, on the other hand.
The resulting list of requirements defines how the product should look like at the end of the design process. Combined with the problem statement this list of requirements leads to the next step of methodical design according to VDI 2221 [VDI83], which covers the description of the basic main functions.

3.1.3 List of Basic Function Structures

This step of methodical design will define the intended basic functions of the final product as well as their classification as main functions and sub-functions. This step is necessary in order to define the basic behaviour and constraints for further design realization.

3.1.4 Definition of Basic Solution

Within this step, all previous taken constraints and approaches are summed up to a concept of the basic solution. That includes a rough overview of the main tasks and features of the final product. The result will be used as a basis for the following steps of the design process.

3.1.5 Modularizations and Partial Pre-Design of Modules

Before diving into further concretization phases of the design process, the potential product needs to be split up into modules, which are decisive for further design and conception steps. Further, within this chapter, that modules will be predesigned. This pre-design only includes the rudimentary boundary conditions of the single modules, including dimensioning and primary function as a base for detailed design steps in further chapters [VDI83, p19] Furthermore, manufacturability and material selection is explicitly not part of this design step.

3.1.5.1 Definition of Multi-Attribute Utility Analysis

During the phase of pre-designing, multi-attribute utility analysis will be applied. The purpose of using this method is to create comparability of design variants according to the compatibility of the product to the tasks.
To describe the method of multi-attribute utility analysis, the term itself needs to be defined and explained.

<u>Definition of multi-attribute utility analysis:</u>
"Multi-attribute utility analysis (MAUA) is used to define the attributes importance in a given decision to create value, based on the summation of the subjective assessment of these attributes" [BL13, p67]

MAUA will be used in this thesis in order to identify, value and evaluate the characteristics and features of the design variants to compare them. The evaluation of the variants includes their objective grading and allows an objective ranking according to suitability and applicability to the task of the product.

3.1.5.2 Pairwise Comparison

Pairwise comparison can be used for comparing each attribute of a system to each other to find out which ones are the most relevant for the finding process of an optimal solution. The result of this method is the percentage distribution of the importance of every single attribute.

In figure 20, ten different attributes have been compared to each other exemplarily, "1" indicates that the attribute shown in line is more important than the attribute shown in the column. "0" indicates that the attribute shown in line is less important than the attribute shown in the column. The weight of every single attribute is listed in the last column.

	\	A	B	C	D	E	F	G	H	I	J	Σ	share
attribute A	A	\	0	1	0	1	0	1	0	1	0	4	8,89%
attribute B	B	1	\	1	1	0	0	1	1	0	0	5	11,11%
attribute C	C	0	0	\	1	1	1	0	0	0	1	4	8,89%
attribute D	D	1	0	0	\	1	1	1	1	0	0	5	11,11%
attribute E	E	0	1	0	0	\	0	0	0	1	1	3	6,67%
attribute F	F	1	1	0	0	1	\	1	0	1	0	5	11,11%
attribute G	G	0	0	1	0	1	0	\	1	1	0	4	8,89%
attribute H	H	1	0	1	0	1	1	0	\	1	0	5	11,11%
attribute I	I	0	1	1	1	0	0	0	0	\	1	4	8,89%
attribute J	J	1	1	0	1	0	1	1	1	0	\	6	13,33%

figure 20: pairwise comparison example

3.2 SWOT Analysis

The SWOT (Strengths, Weaknesses, Opportunities and Threats) analysis is a technique which is used to understand the strengths and weaknesses of a system and to identify the opportunities and the threats the system will face. [MIN19]

In this thesis, this method will be used in the discussion section to create an evaluation of the end product (see chapter 5). The method will define strengths and weaknesses which will address the features and tasks of the final product itself, as well as opportunities and threats which will address features and tasks related to the usage of the end product within a potential scenario. This technique will be applied to the end product in the form of a SWOT list with simple lists the potential strengths, weaknesses, opportunities and threats according to the usage of the designed product within potential scenarios.

4 Methodical Design of a PI Pallet System

In this chapter, the methodical design of a PI compatible pallet system will be applied. The design steps for this pallet system will follow the guidelines according to VDI 2221 to VDI 2223. For better traceability and readability please note the description of the single design steps in chapter 3.1.

4.1 Problem Statement and Definition of User Scenarios for a PI Pallet System

The starting point of the methodical design process according to VDI 2221 to VDI 2223 is the definition of a problem statement. In chapter 2.3.3, the present problem, representing the contradictions between PI philosophy and traditional logistics, was outlined. This problem will now be explained in detail.
As mentioned previously, PI explains the function of PI Load Units during their way through the PI Transportation Network. The tools and device used for transport and handle the PI Load Units within the PI Transportation Network are not defined clearly.
This lack of clarification of the role of pallets throughout handling processes within the whole PI Transportation Network does lead to this following problem statements:

- There is no clear role of pallets in PI, including defined scenarios and definition of interfaces to other PI elements.
- The idea of pallet-less handling of goods is not feasible for a broad mass of potential users, such as small and medium sized enterprises (SME), due to the economic effort of implementing a PI compatible infrastructure.
- There is gap between the theory of PI and the current situation in the field of logistics which must be closed.

According to VDI 2221 this problem statement does mark the starting point of the methodical design process of a PI Pallet.
In order to set boundary conditions and constraints for the further development steps, this step of problem description will be expanded by scenario. That allows to define a clear statement about the potential use cases and needs of users of PI.

4.1.1 User Scenario for a PI Pallet System

Based on the description in chapter 3.1.1, this chapter aims to find and describe potential future scenarios for the usage of PI Pallets in the logistics and transport branch.
More precisely, this includes the listing, description and definition of four main user scenarios where a PI Pallet most likely can be used in. Furthermore, related processes, flowcharts and interaction between the PI Pallet, user and other PI elements will be depicted.

4.1.1.1 Phrases and Wording

Within the sector of scenario finding, terms will occur which will not be understandable and traceable without any description. In order to provide clarification, this subchapter defines the phrases and wording for all terms used in this chapter of the user scenario finding. This will raise the comprehensibility and readability of the following content.

a) Single PI Pallet

PI Pallets without any physical connection to other PI Pallets or PI Container within the logistics and transportation process, are called Single PI Pallet in following text passages, regardless of the dimension of the Single PI Pallet.

b) PI Pallet Unit

Two or more Single PI Pallets with a physical connection to each other but without any connection to PI Containers within logistics and transportation process are referred to as PI Pallet Unit in following text passages, regardless of the dimensions and number of Single PI Pallets forming this PI Pallet Unit.

c) PI Palletized Load Unit

PI Pallet Units or Single PI Pallets which are physically connected to one or more PI Containers or any kind of PI compatible load carrier are called PI Palletized Load Units in following text passages, regardless of the dimensions of the PI Pallet Unit as well as the dimension of the connected PI Container or PI compatible load carrier.

Figure 21 exemplarily shows the difference between Single PI Pallet (left), PI Pallet Unit (middle) and PI Palletized Load Unit (right).

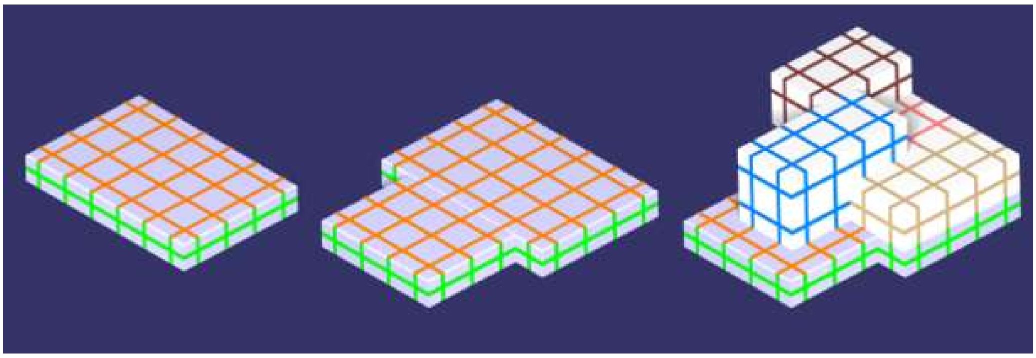


figure 21: handling formats of PI Pallets

The terms of these three basic units that PI Pallets can form during the transport and handling processes can be found again in the following descriptions and flowcharts.

4.1.1.2 Scenarios

In the following, four user scenarios will be defined and described in detail.

Scenario 1: First-Mile Transportation from Manufacturer/Supplier to PI Hub

This scenario addresses the processes beginning with external logistics at the supplier, followed by the first-mile transportation to the PI Hub. After the first-mile transportation, the next process step is the separation of goods at the PI Hub in order to distribute them within the PI Transportation Network. Figure 22 shows the standardized process flowchart for B2B network within PI, which includes the PI Transportation Network as well as the first and the last-mile transportation and related logistics processes at supplier and customer [ELG16]. The red area in figure 22 marks the section this user scenario can be applied to.

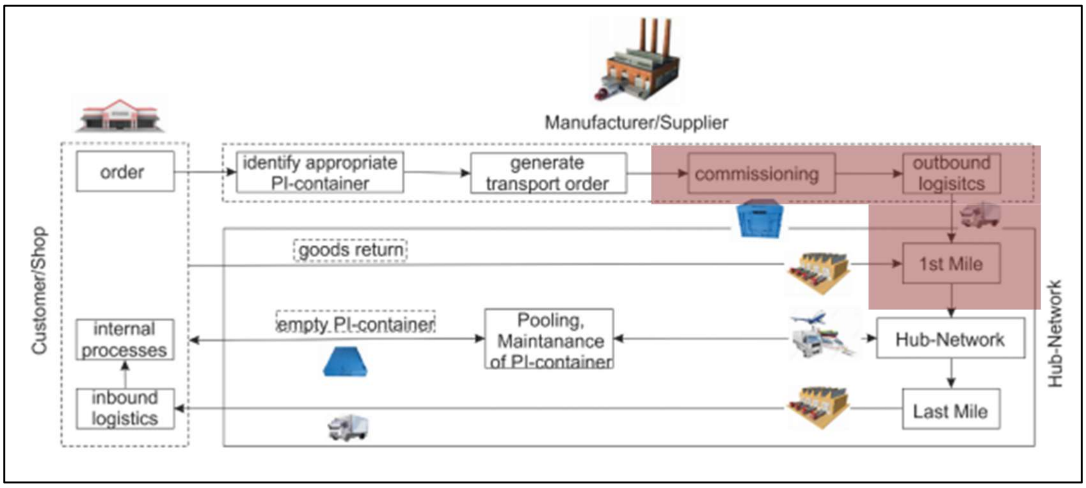


figure 22: standardized process flowchart for B2B network within PI including PI Palletized first mile delivery [ELG16, p6]

<u>Approach</u>:
As mentioned previously, the PI Pallets will be used as load carriers for the PI Containers. As shown in figure 22 goods are encapsulated to PI Container during the external dispatching process at manufacturer/supplier. From that time on the goods need to be handled and transported within this standardized shape. Inside the PI Hub network, PI Containers will be handled in the form of PI Load Units automatically and efficiently with special handling and transport devices. In order to create a modified form of PI Load Units, the PI Pallet can be introduced as a load carrier for the PI Load Units. These resulting PI Palletized Load Units can be handled fast and efficiently with standard handling and transport devices within the external dispatching and packing processes. Single PI Pallets will be connected to a PI Pallet Unit of a suitable format, according to the goods which shall be delivered. By connecting this PI Pallet Unit to the goods, PI Palletized Load Units are formed, which can be handled and transported as one unit with the standard handling devices every manufacturer owns. Goods are already encapsulated to PI Containers at that process step. During transportation, no matter if the transport is services by micro transport devices, trucks or any other transport devices, PI Palletized Load units can be easily locked and secured by using the locking elements, which are placed directly on the bottom of every Single PI Pallet. Summed up, the PI Palletized Load Units will follow the transportation flow within the first-mile transportation from manufacturer/supplier to the first PI Hub where the PI Containers are getting disconnected from PI Pallet Unit. After that, the goods will be distributed within the PI Transportation Network. In this scenario, where the manufacturer only delivers goods, empty PI Pallet Units must be divided into Single PI Pallets and returned to the manufacturer again, in order to close the loop.

Figure 24 shows a flowchart of standardized processes during a possible usage of PI Pallets within first-mile delivery from the manufacturer to the PI Hub. For better readability of this flowchart, please first note figure 23 as a legend for flowchart in figure 24.

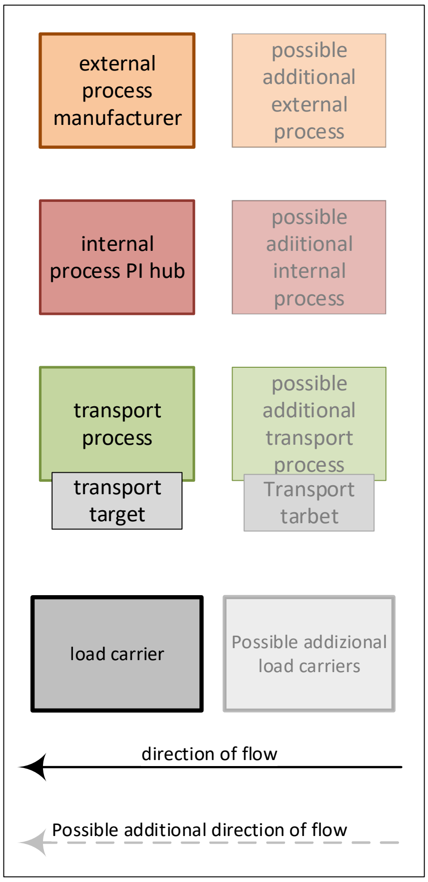


figure 23: flowchart legend for figure 24

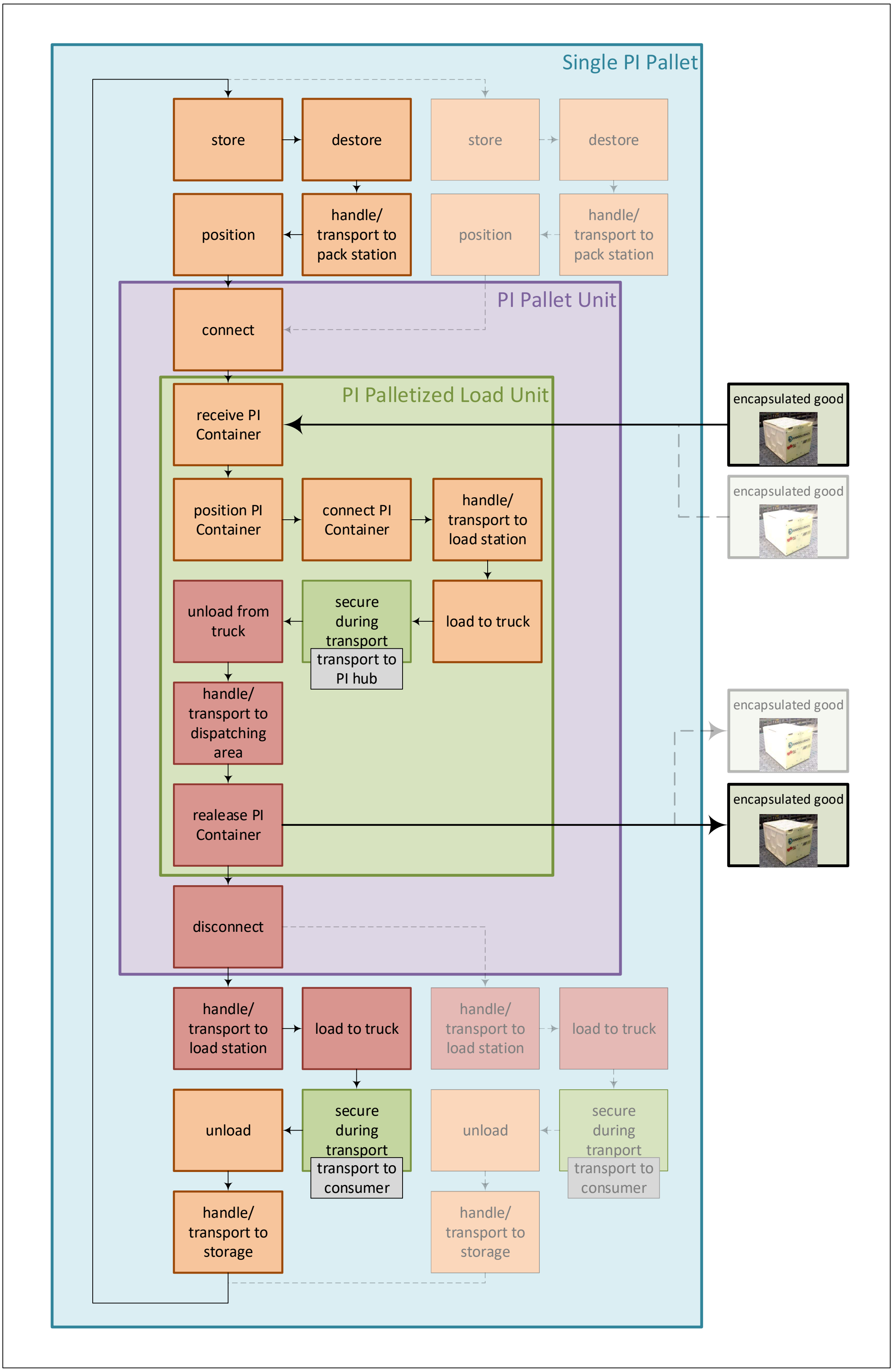


figure 24: flowchart user scenario 1 first mile transportation

Figure 24 shows the main procedure of PI Pallets usage within first-mile transportation. This way of visual illustration does not include any statement about responsibilities and dependencies. In order to expand this chart by showing dependencies and responsibilities during this entire shown process, the procedure has been revised by using the standardized flowchart notation EPC. Figure 26 to figure 28 show the whole process, whereas figure 25 shows the overhead flowchart of the same and provides an overview.
For better readability please note the legends mentioned earlier in chapter 3.1.1.2 first.

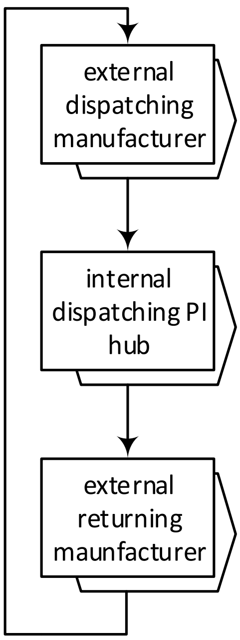


figure 25: overhead EPC process scenario 1

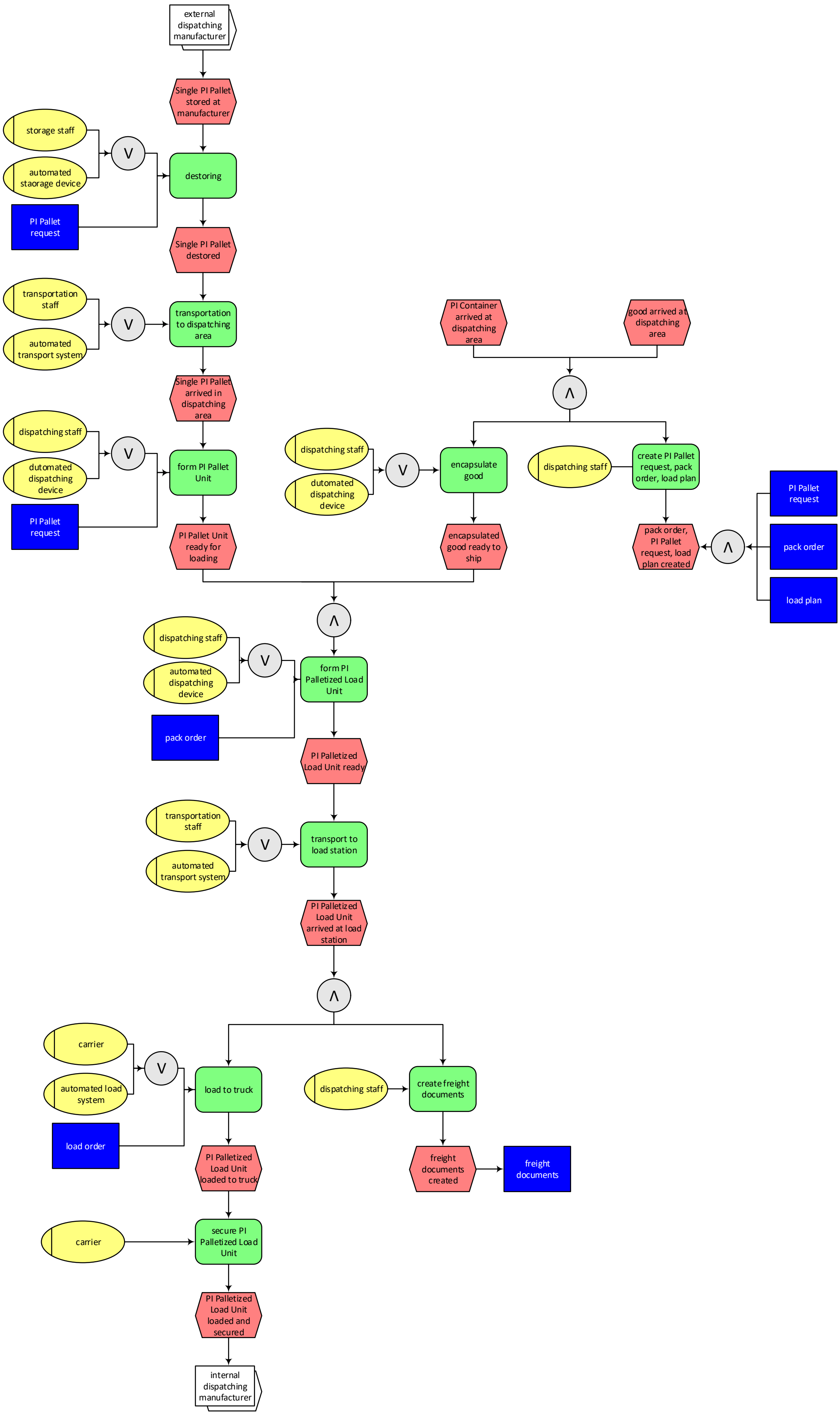


figure 26: EPC process scenario 1 (1/3)

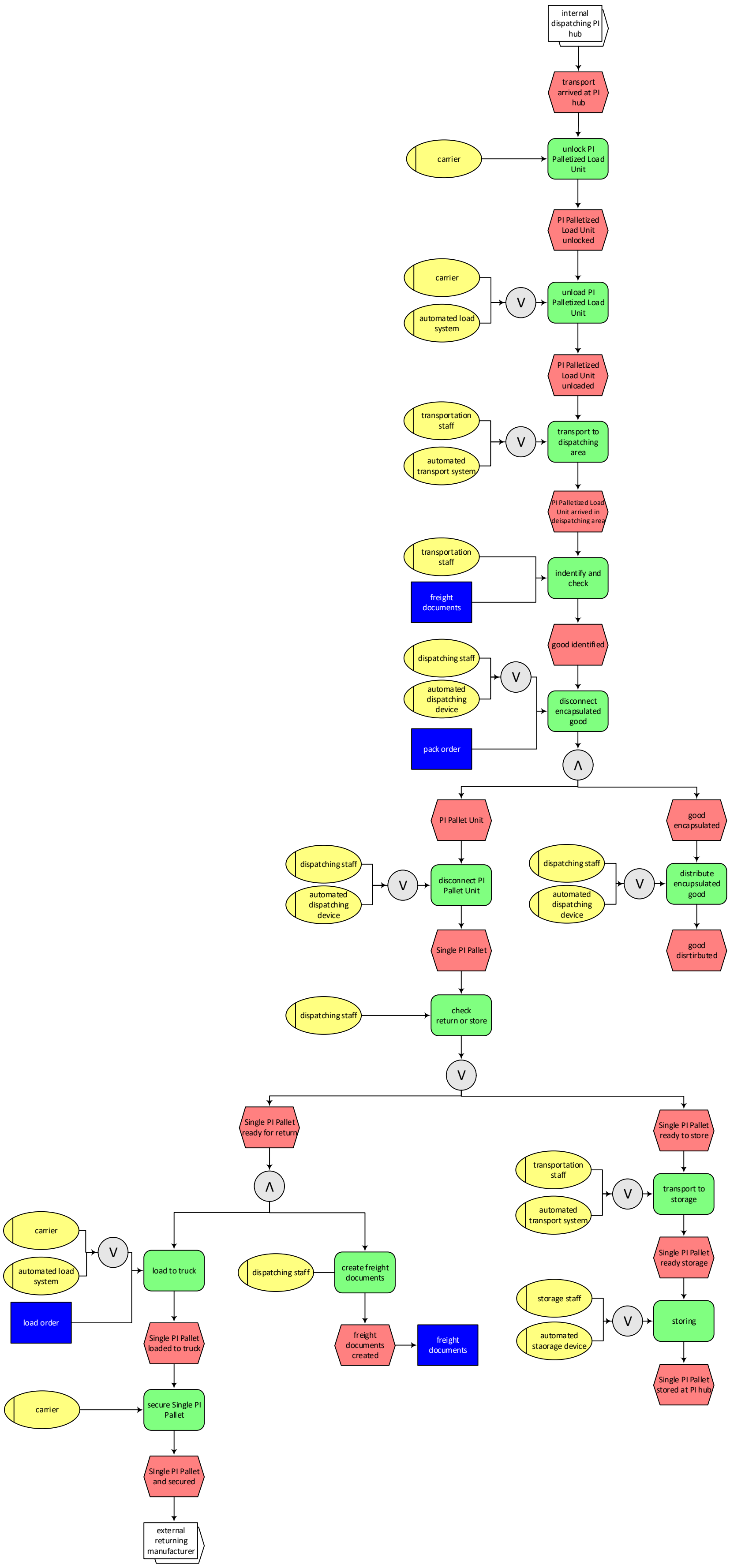


figure 27: EPC process scenario 1 (2/3)

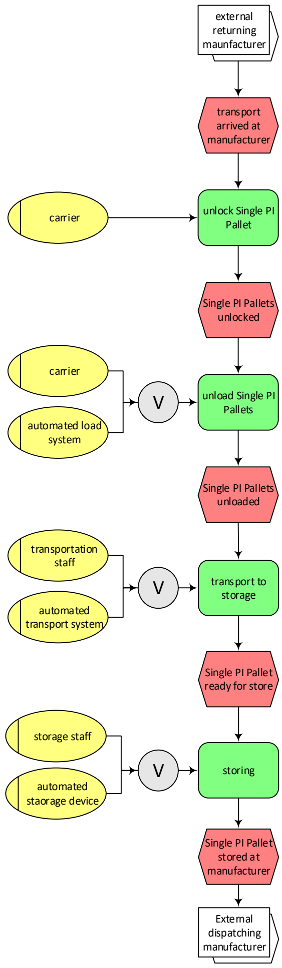


figure 28: EPC process scenario 1 (3/3)

Figure 25 to figure 28 shows the responsibility and executive elements for each process step throughout the whole scenario 1. Most of the single process steps are connected to two different executive elements, one manual and one automated. This shows the flexibility of the usage of PI Pallets during this process according to suitability for automated handling as well as manual handling devices.

Out of the process, shown in figure 25 to figure 28 the following opportunities and weaknesses were developed:

<u>Opportunities and Potential of PI Pallet Usage in User Scenario 1</u>

- Ecological advantages by using PI technology at manufacturer without the need for any special handling devices
- Time-saving potential due to easy handling and locking of the PI Containers during dispatching and transportation processes
- Reducing economic harm by using a standardized locking system included at the PI Pallet
- Economic advantages by saving packing and securing material by using standardized locking system included at PI Pallet

Weaknesses of PI Pallets Usage in User Scenario 1

- need of Single PI Pallet pooling
- loss of transport capacity by returning empty Single PI Pallets
- loss of transport capacity compared to pallet-less transportation because of lost space
- additional effort and workload in PI Hubs

Scenario 2: Last Mile Transportation from PI Hub to a Consumer

This scenario addresses the processes beginning with internal logistics at the PI Hub after distributing the goods through the PI Transportation Network. The next process steps will be the last-mile transportation to the consumer and the external receiving process there. Figure 29 shows the standardized process flowchart for B2B network within PI, which includes the PI Transportation Network as well as first-mile and last-mile transportation and related logistics processes at supplier and customer [ELG16]. The red area in figure 29 marks the section this user scenario can be applied to.

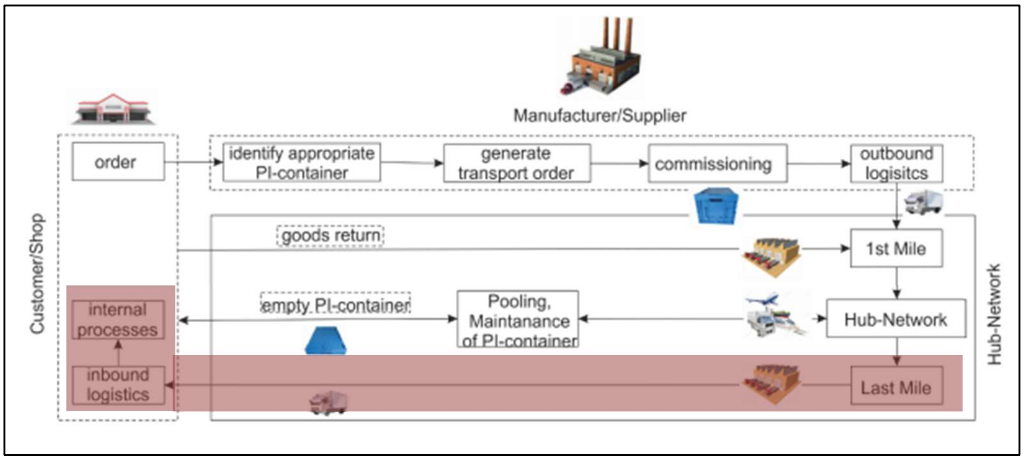


figure 29: standardized process flowchart for B2B network within PI including PI Palletized last mile transportation [ELG16]

Approach:
As mentioned before, Single PI Pallets will be used like in Scenario 1 as load carriers for PI Containers. As shown in figure 29, goods have passed the PI Transportation Network encapsulated in a PI Container until the delivery from the last PI Hub to the consumer. Within the PI Hub network, the PI Containers will be handled automatically and efficiently in the form of PI Load Units with special handling and transport devices. In order to create a modified form of PI Load Units, the PI Pallet can be introduced as a load carrier for the PI Load Units. These resulting PI Palletized Load Units can be handled fast and efficiently with standard handling and transport devices within the external dispatching and packing processes. Analogous to scenario 1, by forming PI Palletized Load Units out of a suitable PI Pallet Unit

and one or more PI Containers, goods can be easily transported to the consumer where they can be handled with standard handling tools. During transportation, no matter if the transport is serviced by micro transport devices, trucks or any other transport devices, PI Palletized Load Units can be easily locked and secured by using locking elements, which are placed directly on the bottom of every Single PI Pallet. To sum this up, PI Palletized Load Units will follow the transportation flow within the last-mile transportation from the PI Hub to the consumer in order to distribute goods there. In this scenario, where the consumer only receives goods, empty PI Pallet Units need to be divided into Single PI Pallets and returned to the PI Hub again, in order to close the loop.

Figure 31 shows a flowchart of the standardized processes during a possible usage of PI Pallets within last-mile delivery from the PI Hub to the customer. For better readability of this flowchart please first note figure 30 as a legend for the flowchart in figure 31.

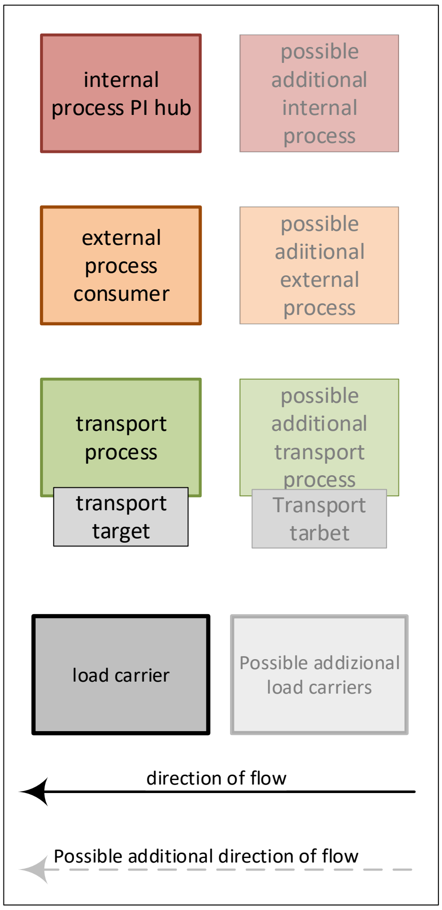


figure 30: flowchart legend for figure 31

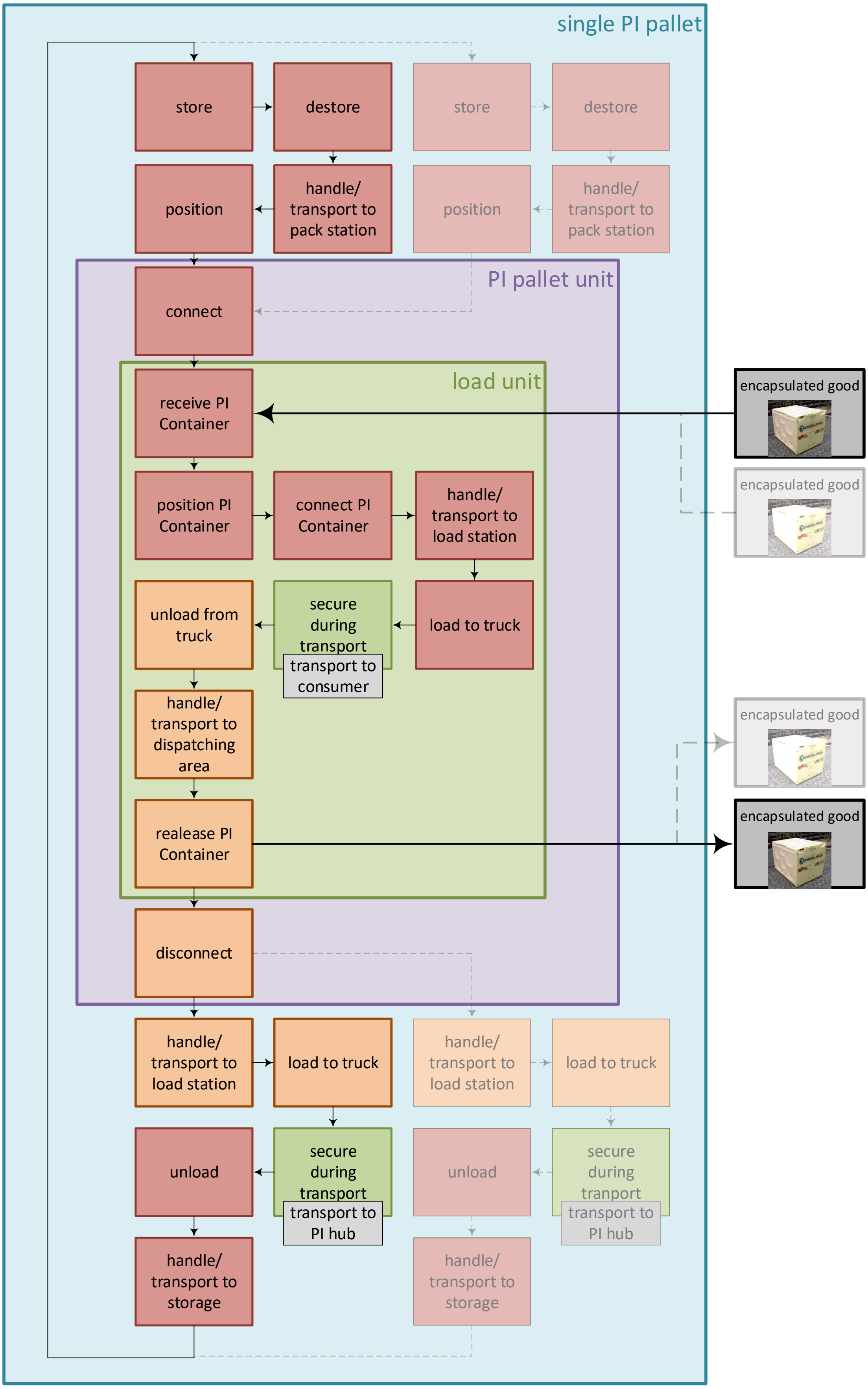


figure 31: flowchart user scenario 2 first mile transportation

Figure 31 shows the main procedure of PI Pallet usage within last-mile transportation. This way of visual illustration does not include a statement about responsibilities and dependencies. In order to expand this chart by showing dependencies and responsibilities during this whole process, the procedure has been revised by using the standardized flowchart notation EPC. Figure 33 to figure 35 show the whole process, whereas figure 32 shows the overhead flowchart of the same and provides an overview.
For better readability please note the legends mentioned previously in chapter 3.1.1.2 first.

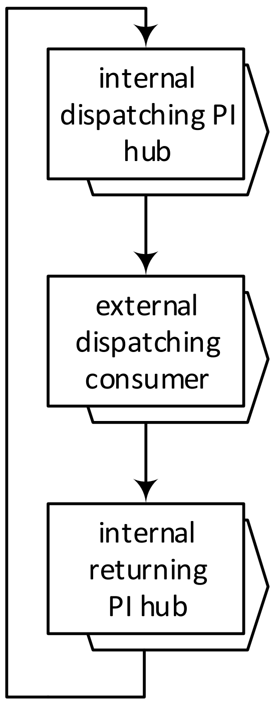


figure 32: overhead EPC process scenario 2

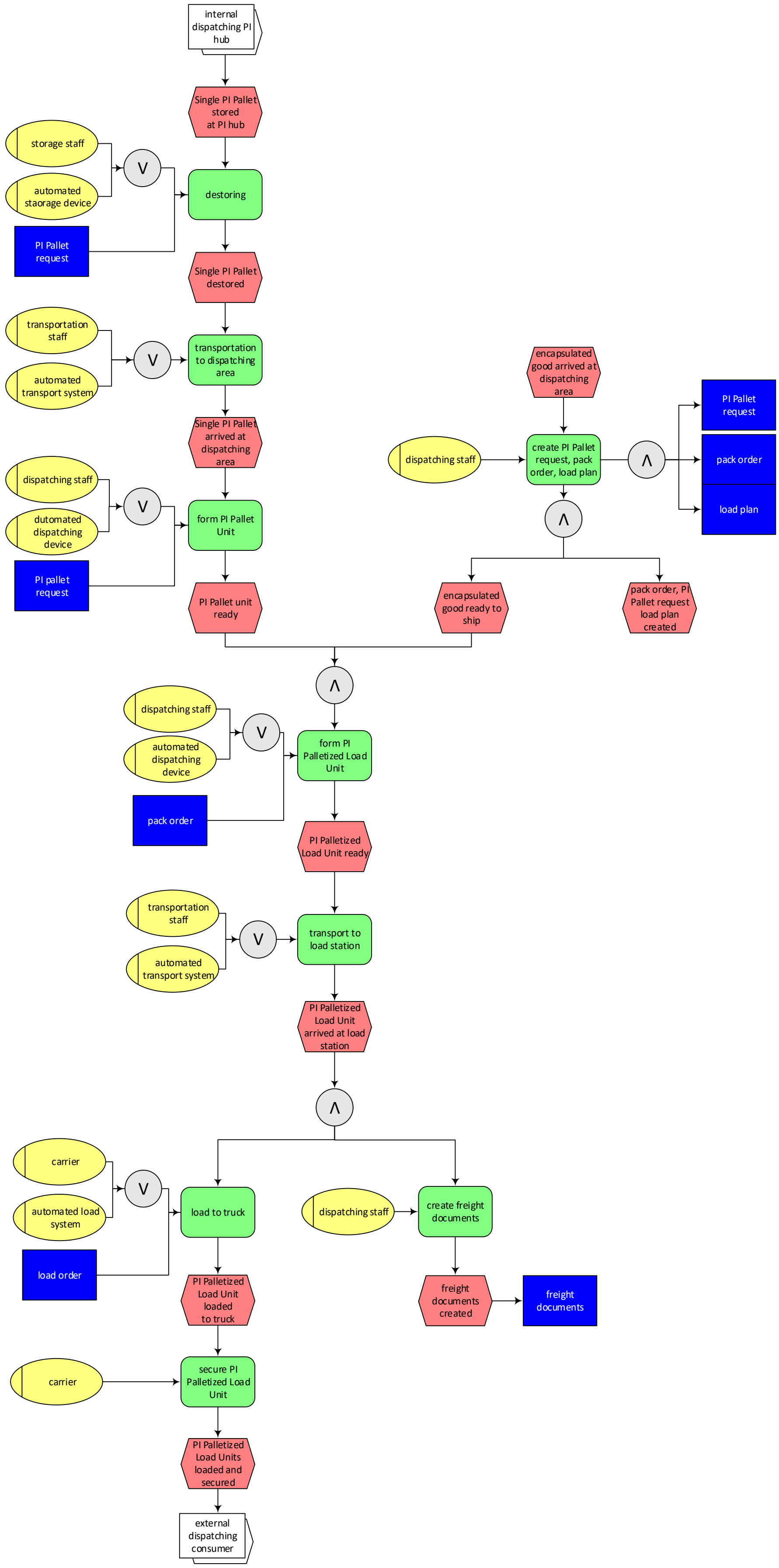


figure 33: EPC process scenario 2 (1/3)

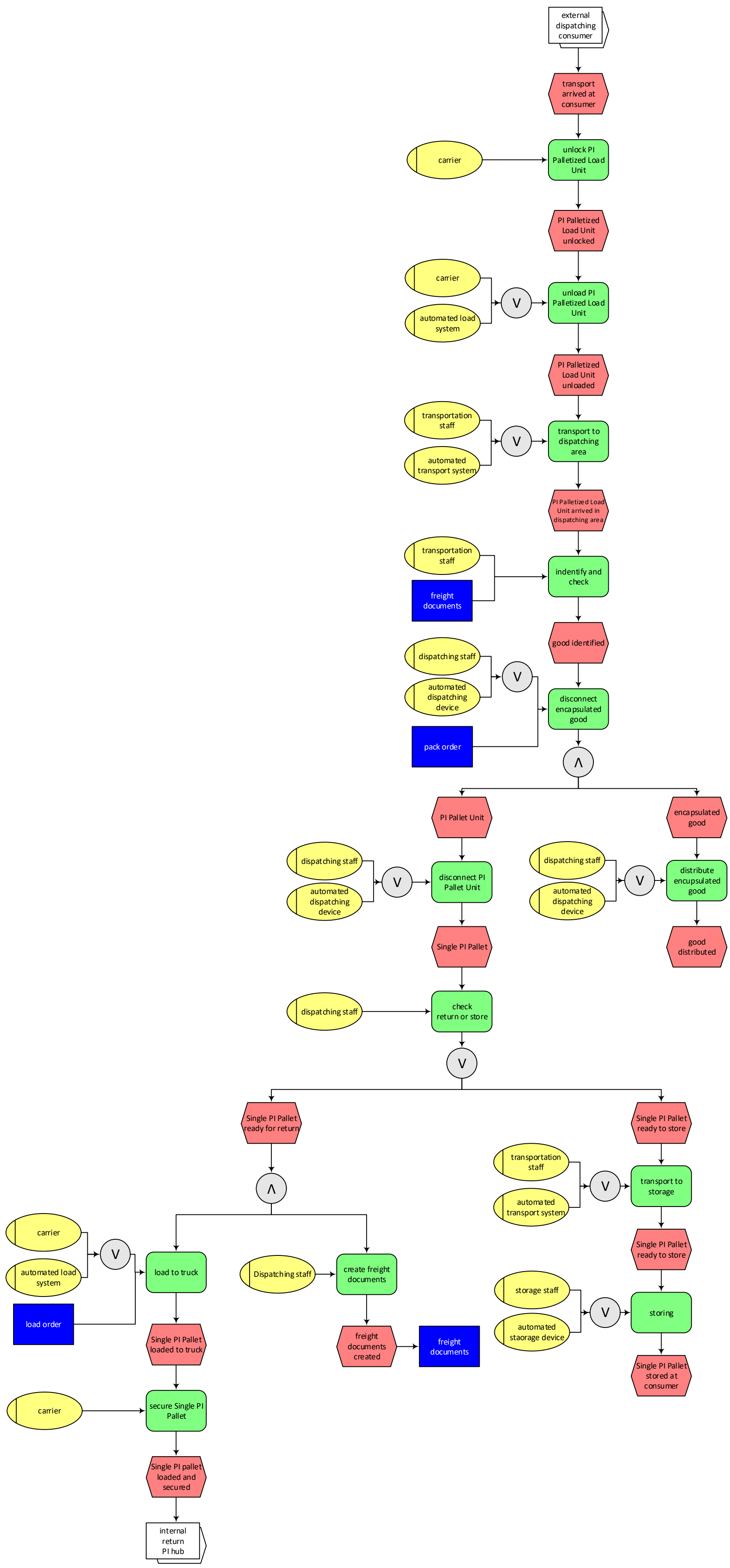


figure 34: EPC process scenario 2 (2/3)

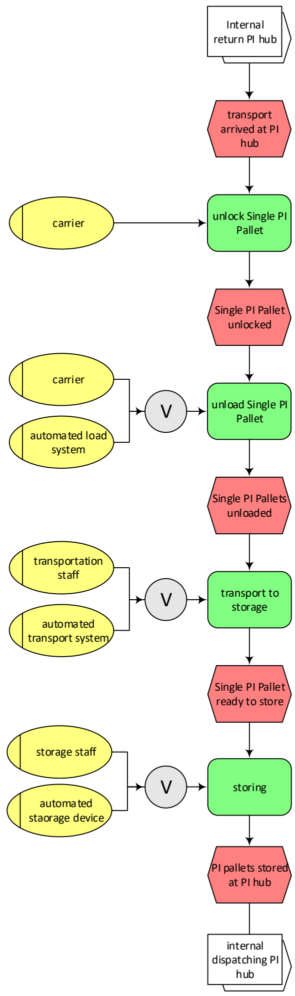


figure 35: EPC process scenario 2 (3/3)

Figure 32 to figure 35 show the responsibility and executive elements for each process step in the entire scenario. Most of the single steps are connected to two different executive elements, one manual and one automated, which shows the flexibility of PI Pallets during this process by suitability for automated handling as well as manual handling devices.

Out of the process, shown in figure 32 to figure 35, the following opportunities and weaknesses were found:

<u>Opportunities and Potential of PI Pallet Usage in User Scenario 2:</u>

- Ecological advantages by using PI technology at consumer without the need for special handling devices
- Time-saving potential because of easy handling and securing PI Containers during dispatching and transportation
- Reduced economic harm by using standardized locking systems attached to PI Pallets
- Economic advantages by saving packing and securing material by using locking systems attached to PI Pallets

Weaknesses of PI Pallet Usage in User Scenario 2

- need of Single PI Pallet pooling
- loss of transport capacity by returning empty Single PI Pallets
- loss of transport capacity compared to pallet-less transportation because of lost space
- additional effort and workload in PI Hubs

Scenario 3: First Mile - Last Mile Loop Transportation

This scenario combines the previously mentioned scenarios of first-mile delivery and last-mile delivery by the usage of PI Pallets within a combined first-mile – last-mile delivery loop. In contrast to scenario 1 and scenario 2, where manufacturers and consumers only send or receive goods, this process is applied to manufacturers as well as consumers which are sending goods and receiving goods during their internal supply chain. In the following text passages, these PI users which receive and send goods are referred to as customers.
Figure 36 shows the standardized process flowchart for a B2B network within PI, which includes the transportation network as well as first-mile and last-mile transportation and the related logistics processes at supplier and consumer [ELG16]. The red area marks the sections to which this user scenario can be applied.

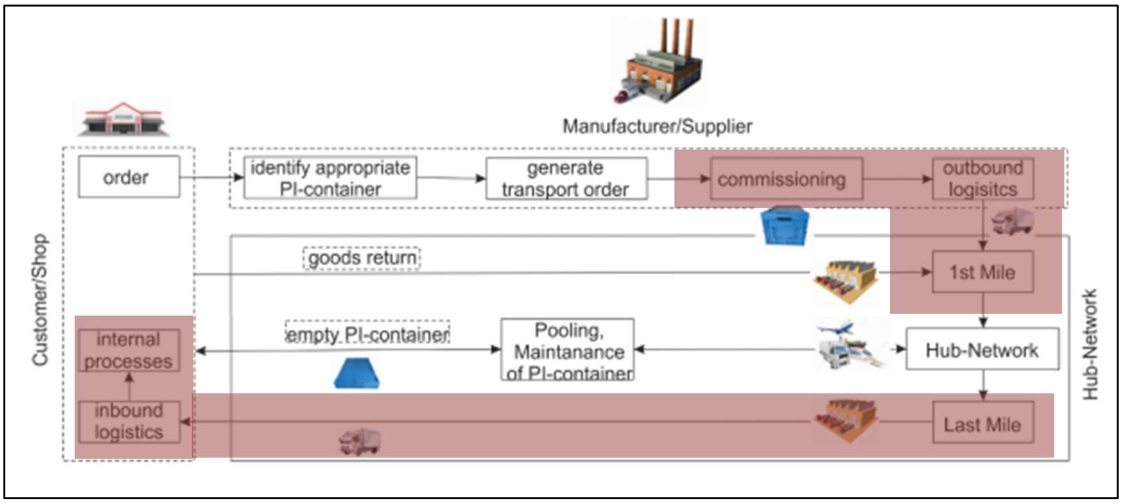


figure 36: standardized process flowchart for B2B network within PI including PI Palletized first mile – last mile transportation loop [ELG16]

As mentioned before, as scenario 3 is a combination of scenario 1 and scenario 2, the basic process steps can be combined as well. The process loop starts at the customer with an external sending process, including forming PI Palletized Load Units out of PI Pallet Units and encapsulated goods. These PI Palletized Load Units will be handled in order to send them within first-mile transportation to the PI Hub. At the first PI Hub goods are separated during an internal receiving process in order to release the goods to the PI Transportation Network. In the next process step, compared to scenario 1, empty Single PI Pallets need to be stored at the PI Hub. Stored Single PI Pallets will be destored in the following again during the internal sending process at the PI Hub. In this sending process, goods, which passed the transportation network, are combined again to PI Palletized Load Units by connecting them to PI Pallet Units. These PI Palletized Load Units will now be sent to the customer within last-mile transportation, regardless or whether the sender at the beginning of this scenario and receiver at the end of this scenario are represented by the same customer or by different customers. At the customer, goods and the Single PI Pallets are separated during an external receiving process. While goods are distributed at the customer, Single PI Pallets are stored, in order to have them ready to use again in the next external sending process which will close the process loop of this scenario.

Figure 38 shows a flowchart of this standardized processes during a possible usage of PI Pallets within this closed first-mile-last-mile transportation loop. For better readability of this flowchart please first note figure 37 as a legend for the flowchart in figure 38.

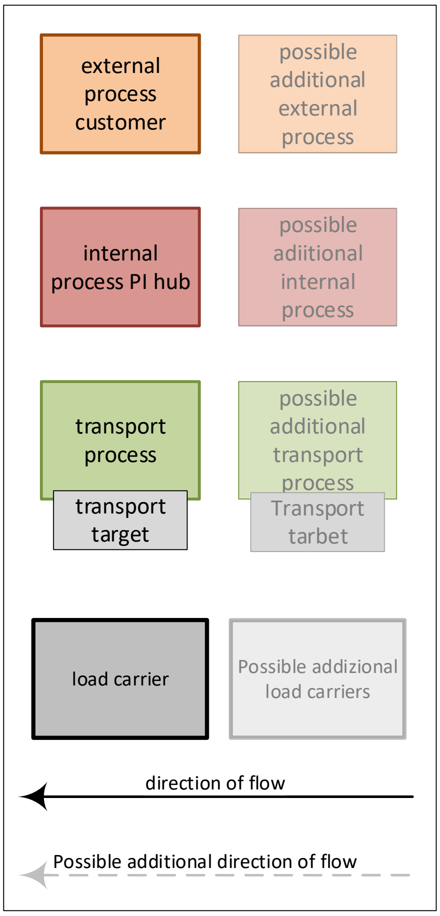


figure 37: flowchart legend for figure 38

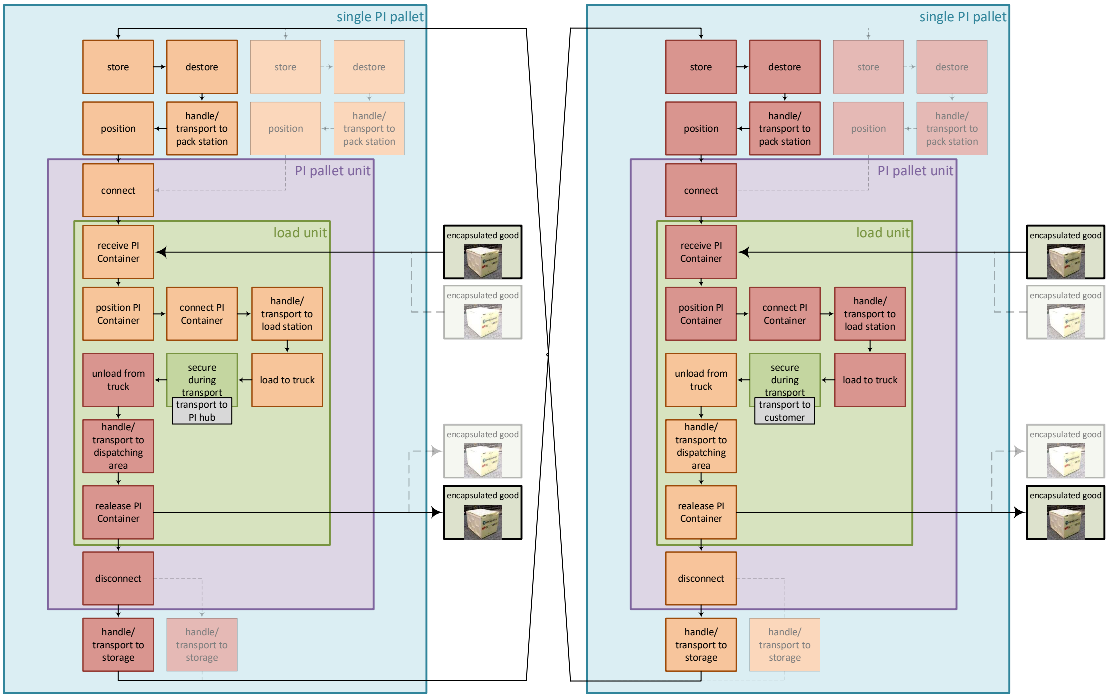


figure 38: flowchart user scenario 3 first mile – last mile transportation loop

Figure 38 shows the main procedure of PI Pallet usage within scenario 3. This way of visual illustration does not include a statement about responsibilities and dependencies. In order to expand this chart by showing dependencies and responsibilities during this whole shown process, the procedure has been revised by using the standardized flowchart notification EPC. figure 40 40 to figure 43 shows the whole process whereas figure 39 shows the overhead flowchart of the same and provides an overview.
For better readability please note the legends mentioned in chapter 3.1.1.2 first.

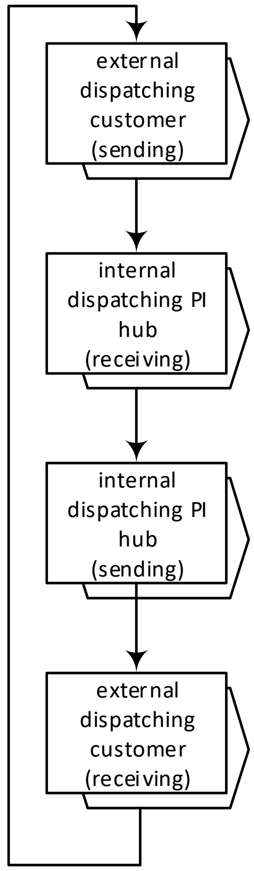


figure 39: overhead EPC process scenario 3

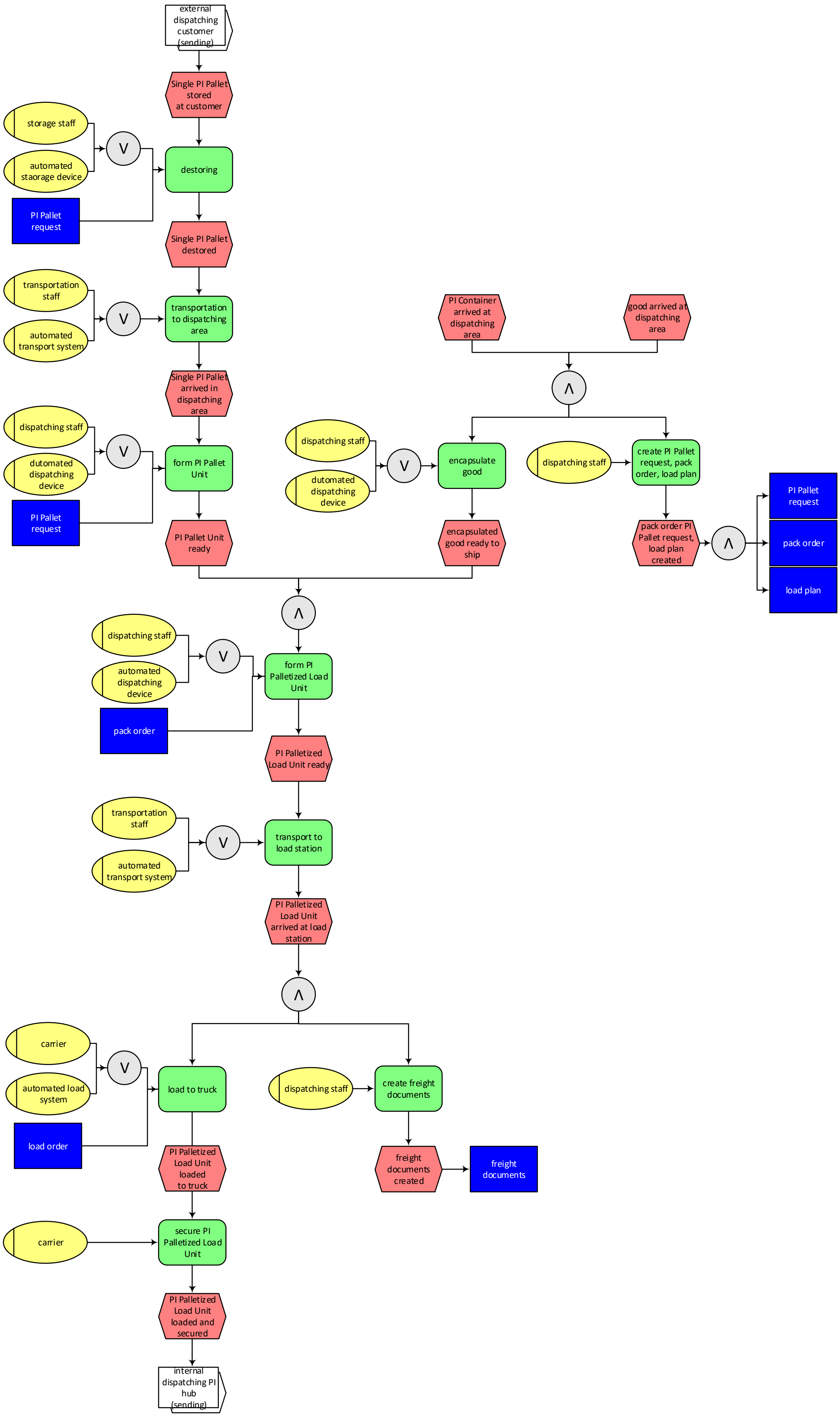


figure 40: EPC process scenario 3 (1/4)

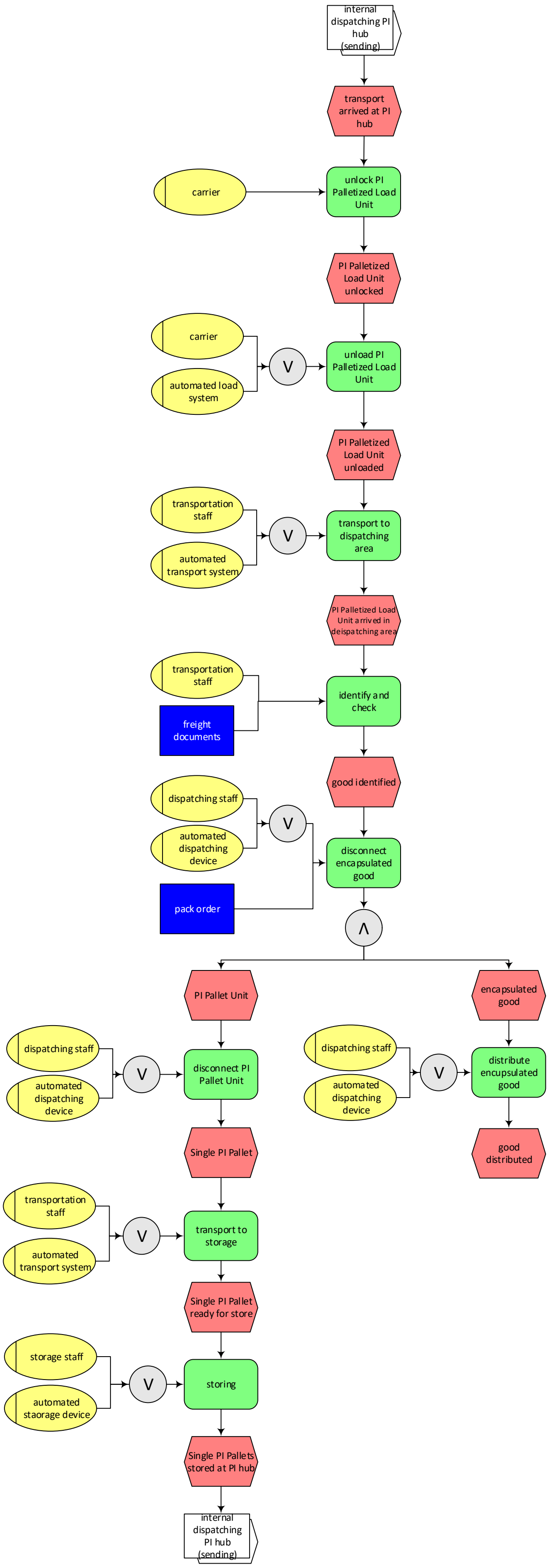


figure 41: EPC process scenario 3 (2/4)

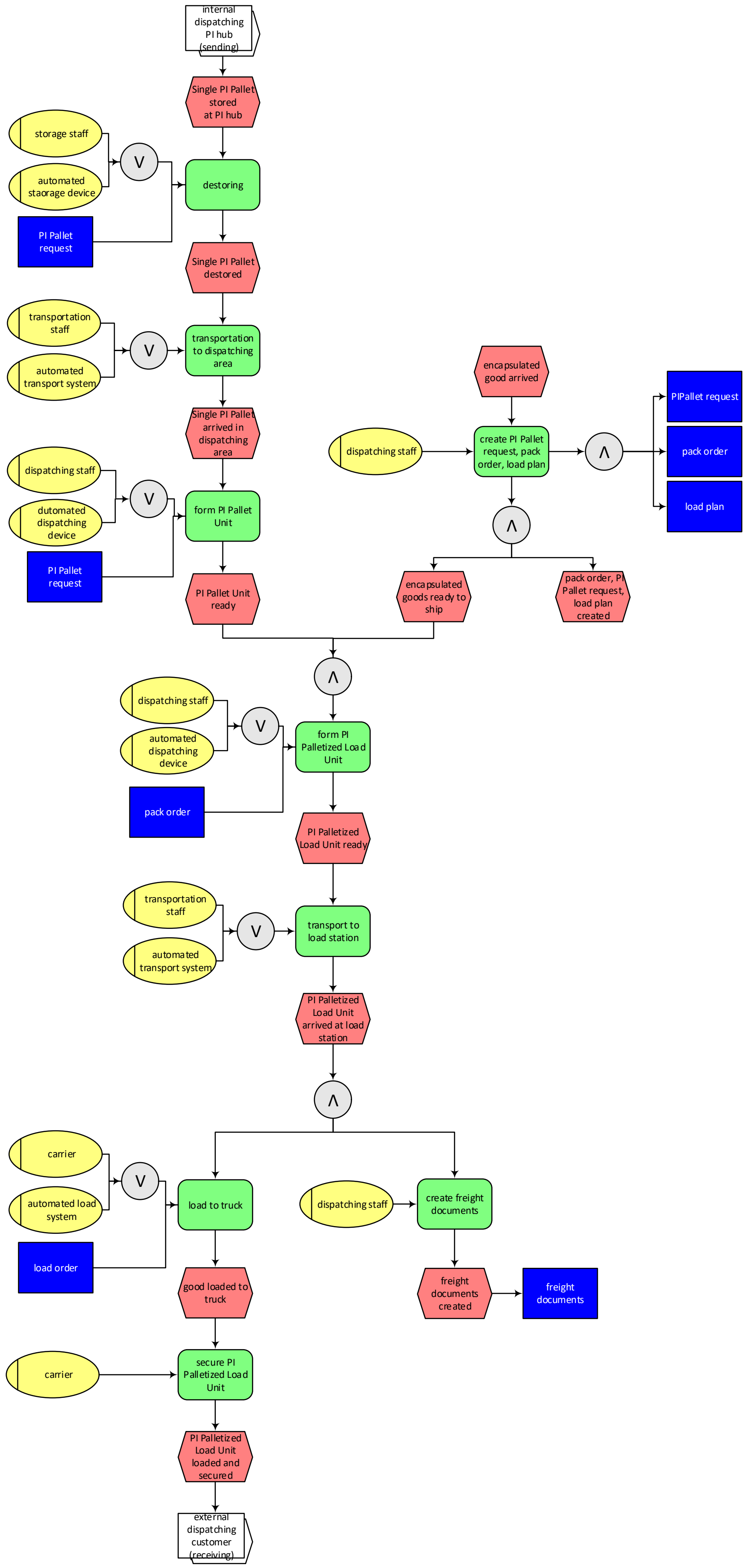


figure 42: EPC process scenario 3 (3/4)

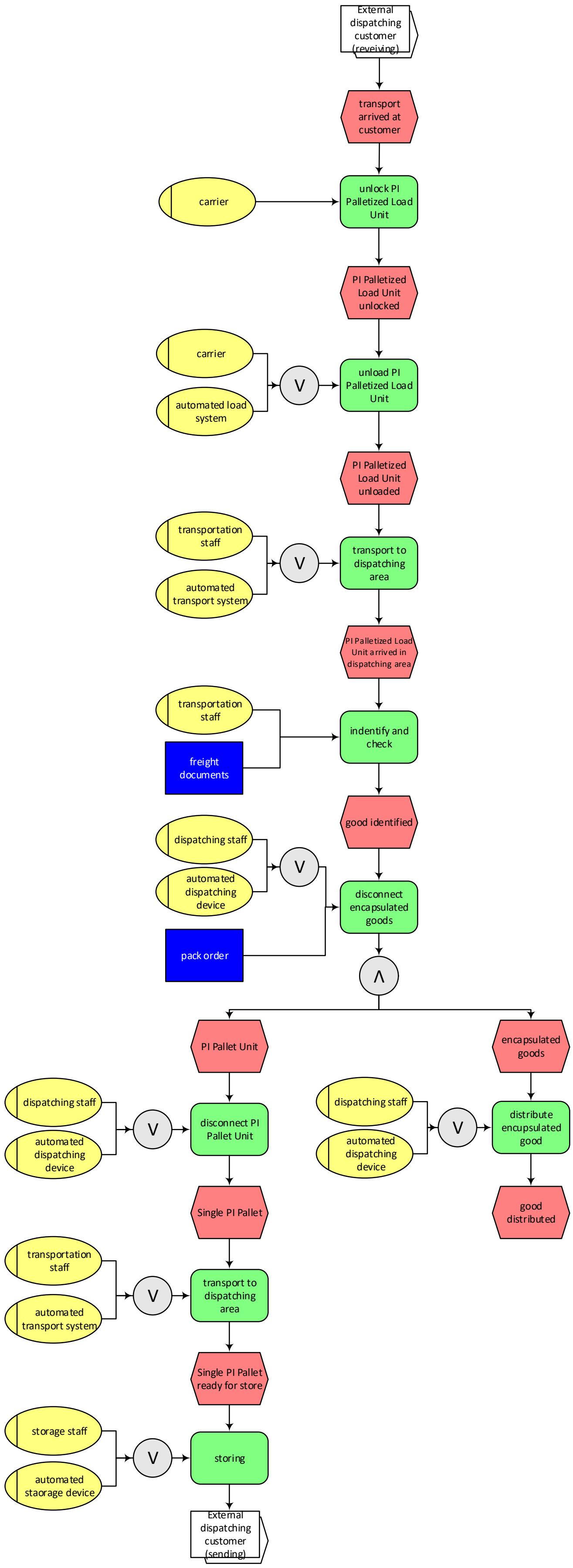


figure 43: EPC process scenario 3 (4/4)

figure 40 40 to figure 43 show the responsibility and executive elements for each process step during this scenario. Most of the single steps are connected to two different executive elements, one manual and one automated. This shows the flexibility of PI Pallets during this process by suitability for automated handling as well as manual handling devices.

Out of the process, shown in figure 40 to figure 43, the following opportunities and weaknesses were developed:

Opportunities and Potential of PI Pallet Usage in User Scenario 3

- Ecological advantages by using PI technology at a customer without the need for special handling devices
- Time-saving potential because of easy handling and securing PI Containers during dispatching and transportation
- Reducing economic harm by using standardized transport locking systems attached to PI Pallets
- Economic advantages by saving packing and securing material by using standardized transport locking systems attached to PI Pallets

Weaknesses of PI Pallet Usage in User Scenario 3

- need of Single PI Pallet pooling
- need for storage for Single PI Pallet at PI Hub
- loss of transport capacity compared to pallet-less transportation because of lost space
- additional effort and workload at PI Hubs

Scenario 4: Special Transportation

This scenario addresses special transportations, e.g. heavy good transportation or long material transportation. Nowadays, special fitted one-way pallets are a wide-spread tool for transporting goods with special dimensions. Due to the background of economical thinking, PI Pallets, which can be used flexibly for transporting various goods of different sizes by simply and easily forming differently shaped PI Pallet Units out of Single PI Pallets, may can replace one-way pallets for transport and handling tasks of special goods.

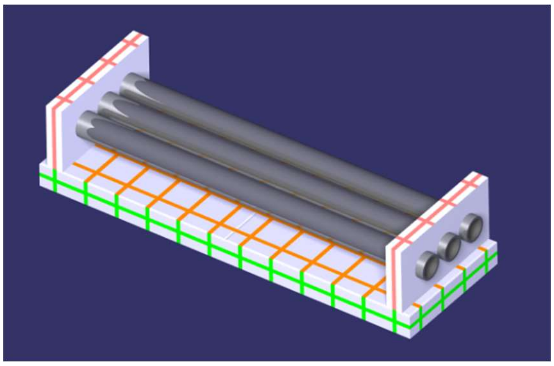


figure 44: special good transportation with PI Pallets

Figure 44 exemplarily shows the concept of special good transportation supported by usage of a PI Pallet system. As shown in the picture, goods with special dimensions can be easily locked and secured by flexible positionable and PI Pallet compatible load carriers. This will make securing and fixation tasks of these goods easier during transportation.
This scenario does not implicitly address the field of PI because of difficulties with encapsulating goods of special dimensions and behaviour. Special goods will probably always be transported via special transport processes, but this scenario shows one more possible niche of the logistics branch, where PI Pallet may be used in the future.

Opportunities and Potential of PI Pallet Usage in User Scenario 4

- Optimized space utilization level during transportation of special goods
- Ecological advantages by removing of one-way pallets
- Economical advantages due to simple securing and locking processes
- Flexible multi-usage of Single PI Pallet for different good dimensions

Weaknesses of PI Pallet Usage in User Scenario 4

- need of Single PI Pallet pooling
- loss of transport capacity due to space required for used PI Pallet Units

4.1.2 List of Requirements for a PI Pallet

In chapter 4.1.1, the potential usage of PI Pallets in four scenarios in the logistics and transport section has been outlined. The next step in the process of methodical design according to VDI 2221, as mentioned in chapter 3.1.2, is the definition of requirements for the final product, a PI Pallet.
table 1 sums up all requirements from different sources in order to form a list of requirements applied to a PI Pallet used in scenarios defined in chapter 4.1.1. This table shows the characteristics of all requirements as well as a short description. For a detailed description of every requirement please note the text passage below the table.

table 1: list of requirements

no	constraint/wish	implicit/explicit	requirement	comment
1	constraint	implicit	minimum weight	legal issues
2	constraint	implicit	high load capacity	> 4000kg static, > 1500kg dynamic (for 1200x800mm)
3	constraint	implicit	ergonomic and safe	according to the state of the art
4	constraint	implicit	interconnectable PI Pallet/PI Container	different PI Container dimensions
5	constraint	implicit	interconnectable PI Pallet/PI Pallet	in appropriate positions
6	constraint	implicit	modular dimensions	different variants
7	constraint	explicit	suitable for fork lifts handling	standard fork lift dimensions
8	constraint	explicit	suitable for automated handling	fully automation
9	constraint	explicit	transport lock implementation	included transport lock elements
10	wish	implicit	minimal heigth	minimal heigth relevant
11	wish	implicit	reusable	mulitusing
12	wish	implicit	low maintainance	no electricity for mechanism
13	wish	implicit	recycleable	recycleable material, recycleable elements
14	wish	explicit	stackable	pallet to pallet
15	wish	explicit	flexibility	suitable for different containers/goods
16	wish	explicit	implemantation of digitalisation	tracking, identification, communication,...
17	wish	explicit	implemantation of condition monitoring	acceleration, temperature, load,...

1. PI Pallets must weigh as little as possible. Due to legal issues, the maximum of reasonable workload for workers must not be exceeded. [ASG19]
2. PI Pallets must fulfil at least the same mechanical tasks as a standard Pallet used nowadays in the transport section does. Due to standards, EURO Pallets can hold 4.000kg static load and 1.500kg dynamic load [MMS06, p67]
3. PI Pallets must be designed in a way which reduces the risk of injuries to a minimum and manual handling processes must be as ergonomic as possible. PI Pallets need to fulfil all related legal standards, e.g. no sharp edges.
4. PI Pallets must be able to hold one or more PI Containers of different size in order to form a PI Palletized Load Unit.
5. PI Pallets must be able to be connected to one or more PI Pallets in order to form a PI Pallet Unit.
6. PI Pallets must be available in modular dimensions, defined by divisibility by the smallest modular unit of length and the width.
7. PI Pallets must be able to be handled manually by forklifts with standard dimensions.
8. PI Pallets must be able to be handled, transported and operated by a fully automated handling and transport devices, e.g. belt conveyors.
9. PI Pallets must have included transport locking elements where the PI Pallet can be secured and locked at the transport unit during transportation.
10. PI Pallets should require as little space as possible. Due to the modularity of length and width, the relevant dimension is the height of the PI Pallet. As a reference, the height of a EURO Pallet used nowadays in the transport section can be considered. Due to standards, EURO Pallets usually have a height of 144mm [HK15, 135]
11. PI Pallets should be able to be used multiple times during its lifespan.
12. PI Pallets should require a minimal maintenance. This includes mechanical maintenance according to wear as well as a mechanism operated without electric power.

13. PI Pallets should be recyclable. This includes the recycling of materials the PI Pallet is made of as well as parts and modules of the PI Pallet.
14. PI Pallets should be easily stackable with a minimum of wasted space.
15. PI Pallets should be able to interact with different forms of PI Containers and compatible load carrier systems. This includes the connectivity to PI Containers using different interlocking mechanisms.
16. PI Pallets should be able to implement features of the megatrend digitalization. This includes exemplary functions and features for tracking, identification and communication.
17. PI Pallets should be able to implement features of condition monitoring. This includes functions and features for gathering, process and spread information about physical conditions, e.g. temperature.

These requirements define how the final product should look and function at the end of the design process. Combined with the problem statement, which was expanded by the method of scenario writing (see chapter 4.1.1), this list of requirements leads to the next step of methodical design according to VDI 2221, which covers the description of main functions.

4.2 List of Basic Functional Concepts of a PI Pallet

In the previous chapters 4.1.1 and 4.1.2, user scenarios as well as requirements for a PI Pallet used during potential PI implemented logistics and transport processes has been figured out. According to the description in chapter 3.1.3, this process step defines the functions of a PI Pallet that need to be fulfilled in order to be compatible with user scenarios and defined requirements.
In order to split up these functions, five groups of main functions have been formed:

- Interconnection between PI Pallet and PI Container
- Interconnection between two or more PI Pallets
- Interconnection between PI Pallet and transport unit, no matter which kind of transport unit
- Handling processes by manual handling devices as well as automated handling devices
- Digitalization by providing a place as well as interfaces for elements of the upcoming megatrend digitalization, including communication and condition monitoring devices

Figure 45 shows these five main functions as well as a breakdown of each main task to several sub-functions.

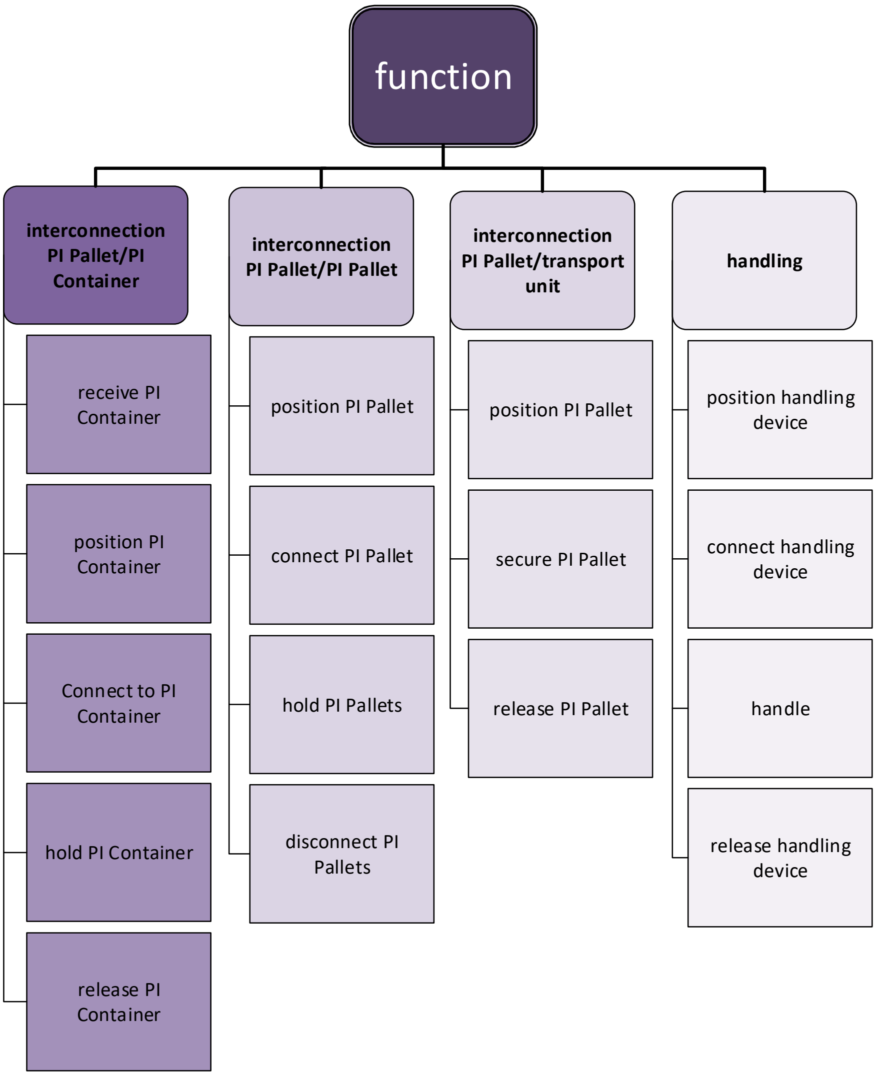


figure 45: list of functions of PI Pallet

For further design and development steps, this table of functions, besides the list of requirements defined in chapter 4.1.2, will be used as a basis. For the development process in this thesis, the two following constraints according to the table of function have been made, which allows simplifying the design process and enables the focus on the most important features and tasks during this stage of prototype development:

- It is assumed that automated handling devices that are handling the PI Pallet in potential future scenarios, take the mechanism as a basis which is used for forming the interconnection between two or more PI Pallets. Manual handling devices (e.g. forklifts) are not being influenced by this restriction.
- Digitalization is mentioned within the list of requirements as well as the function table for reasons of completeness and will not be fully included in this thesis' following design process of a PI Pallet. Implementation of digitalization is not the core topic of this thesis and may be the topic of additional projects or theses.

4.3 Definition of a Basic Solution for a PI Pallet

According to the description in section 3.1.4., the content of this chapter includes the definition of the main tasks for the PI Pallet. The definition of these tasks is based on the functional structure defined in chapter 4.2. Figure 46 as well as the text below shows and describes these defined main tasks. The definition and description will follow the assumptions taken in chapter 4.2

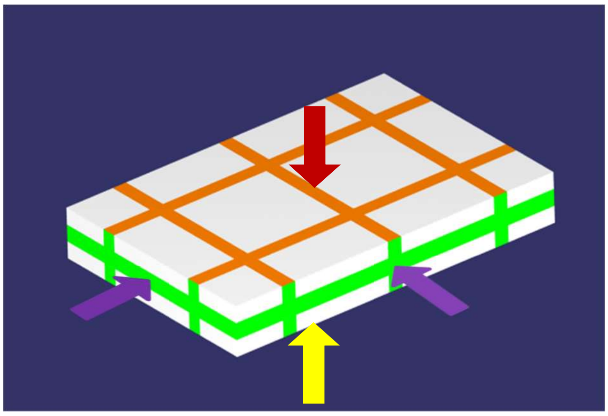


figure 46: Basic solution of PI Pallet

- the purple arrows in figure 46 ( ) represent the interconnectivity between two or more PI Pallets as well as the handling by an automated handling device.
- the red arrow in figure 46 ( ) represents the interconnectivity be-tween PI Pallets and one or more PI Containers or PI compatible load carriers.
- the yellow arrow in figure 46 ( ) represents the interconnectivity and locking between PI Pallets and the transport device as well as the handling by a manual handling device. (e.g. forklift).

4.3.1 Modularizations and Partial Design of a PI Pallet

According to the description in chapter 3.1.5, within the next step of further concretization of the design, the potential final product needs to be split up into design and conception decisive modules.
In the case of PI Pallet, this product has been split up into three modules:

- Base part
- Inlay part
- Top part

In figure 47, this separation is shown in graphical form.

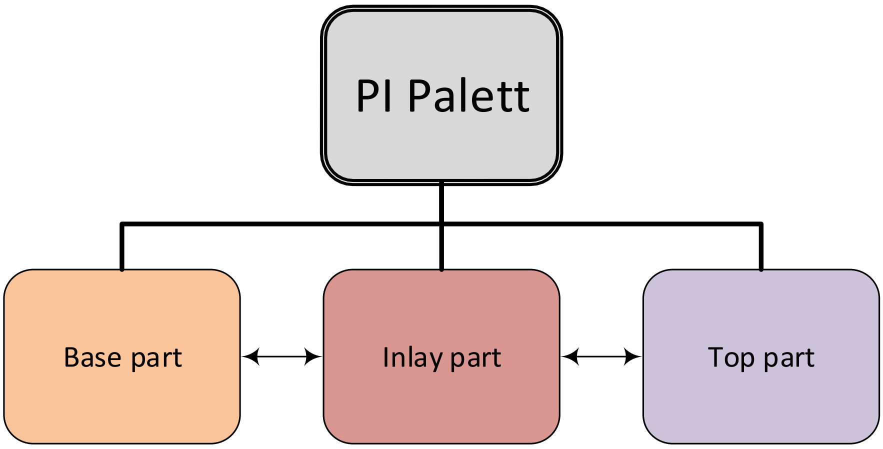


figure 47: modular structure of PI Pallet

These three modules need to be developed separately according to special tasks, design and features. When assembled, the modules form a PI Pallet with all its resulting features and design details.
In order to specify basic functions, border conditions and dimensions of the modules, functions and requirements need to be allocated to the single modules. This allocation follows the basic solution and basic tasks according to figure 46.
table 2 shows the list of requirements (see 4.1.2) as well as a specification to which module they can be allocated to, complemented by the categorized functions (see 4.2) depicted in figure 48.

table 2: modified list of requirements

	relevance		
requirement	Base Part	Inlay Part	Top Part
minimum weight	✓	✓	✓
high load capacity	✓		✓
ergonomic and safe	✓	✓	✓
interconnectable PI Pallet/PI Container			✓
interconnectable PI Pallet/PI Pallet	✓	✓	
modular dimensions	✓	✓	✓
suitable for fork lifts handling	✓		
suitable for automated handling	✓	✓	
transport lock implementation	✓		
minimal heigth	✓		✓
reusable	✓	✓	✓
low maintainance		✓	
recycleable	✓	✓	✓
stackable	✓		✓
flexibility			✓

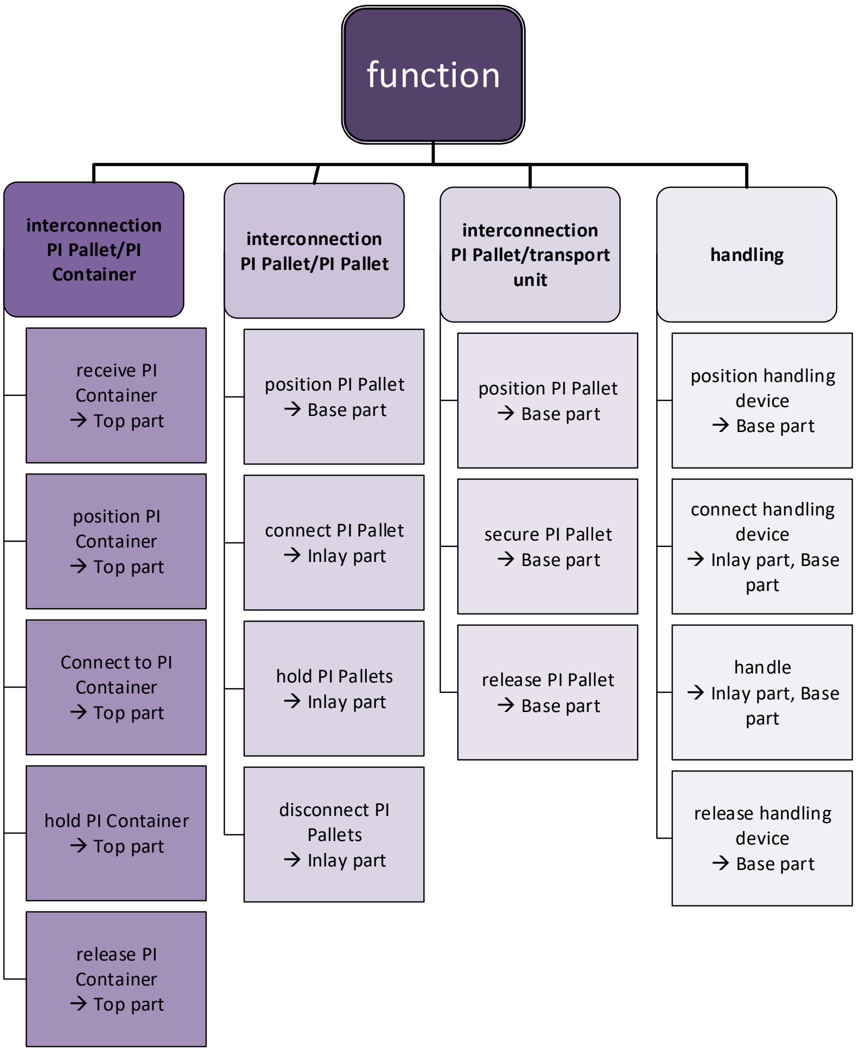


figure 48: modified function table

The rough design presented in this chapter, will not cover all requirements and functions listed in table 2 and figure 48. As mentioned before, this module design, which will be outlined in the following, covers the most important and crucial functions and requirements according to the main dimensions and design variant.

4.3.2 Pre-design of the Base Part

The design and the dimensions of the base part define most of the design and the dimension of the end product. Therefore, the base part is the first module that must be outlined.
The outcome of this process step will be the rough design of different modular PI Pallet dimensions.
The main approach of creating modular dimensions of PI Pallets is the divisibility of the lengths and width by the lowest common divisor. Figure 49 shows different variants and shapes of modular dimensions of a rectangular element, based on the lowest common divisor, represented as x.

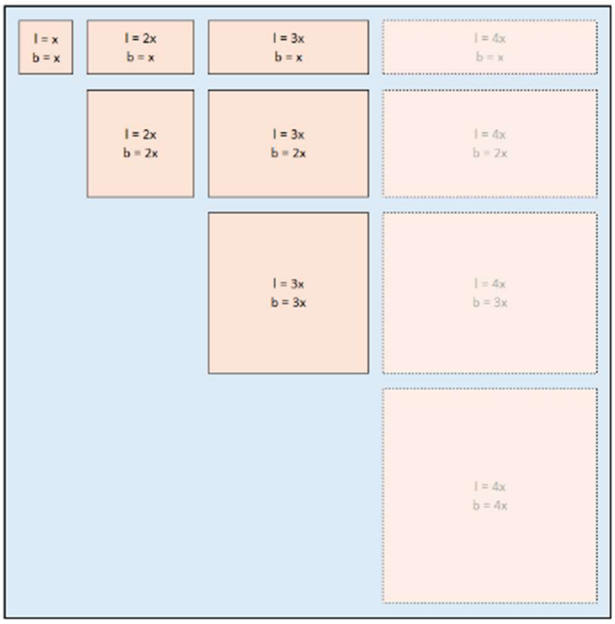
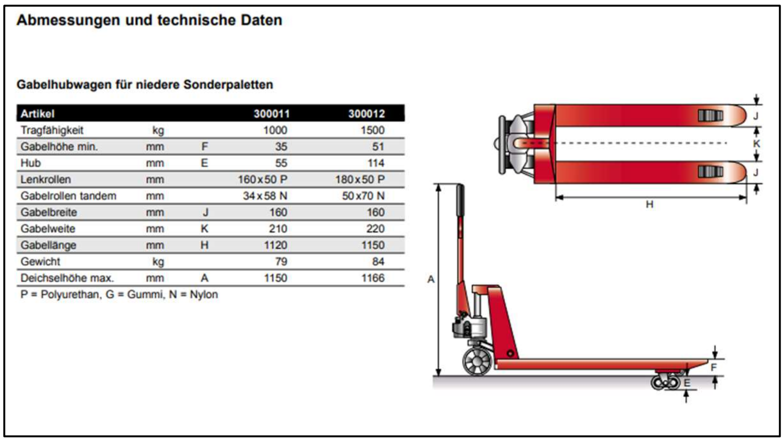


figure 49: general modular dimension based on lowest common divisor x

One of the features of the PI Pallets is the transportability by forklifts. Due to that, the dimensions will be mainly defined by the dimensions of standard forklifts, which are shown in figure 50.



Abmessungen und technische Daten

Gabelhubwagen für niedere Sonderpaletten

Artikel			300011	300012
Tragfähigkeit	kg		1000	1500
Gabelhöhe min.	mm	F	35	51
Hub	mm	E	55	114
Lenkrollen	mm		160x50 P	180x50 P
Gabelrollen tandem	mm		34x58 N	50x70 N
Gabelbreite	mm	J	160	160
Gabelweite	mm	K	210	220
Gabellänge	mm	H	1120	1150
Gewicht	kg		79	84
Deichselhöhe max.	mm	A	1150	1166

P = Polyurethan, G = Gummi, N = Nylon

figure 50: forklift dimensions [WAG19]

In order to find modular dimensions suitable for forklift handling, the lowest common divisor x (see figure 49) must be defined by forklift dimensions. As the width of the forks (J) is 160mm and the distance between forks (K) is 220mm to 210mm, the value for the lowest common divisor for creating modular dimension is set on 400mm. Potential modular dimensions for PI Pallets by setting values of length and width to a multiple of 400 can be seen in figure 51.

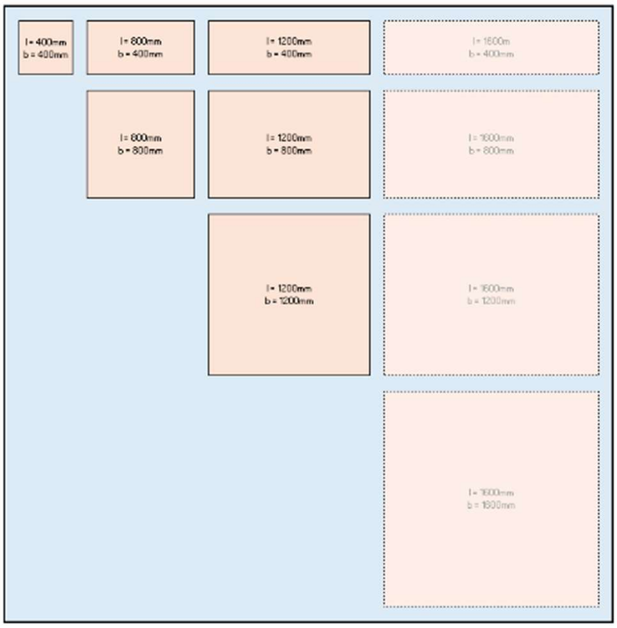


figure 51: general modular dimension based on lowest common divisor 400mm

These variants of modular dimensions could be extended to infinity as implied in figure 51. For this thesis the focus is on the first six variants of dimensions which are:

- 400mm x 400mm
- 400mm x 800mm
- 400mm x 1200mm
- 800mm x 800mm
- 800mm x 1200mm
- 1200mm x 1200mm.

The variant 800mm x 1200mm is equal to the standard dimension of widely spread EURO Pallets [HK15, p135]. This fact leads to the previous decision to focus on the remaining six variants. All other conceivable dimensions, due to rules presented in figure 49, can easily be formed by combining two or more of the variants chosen for further considerations.

In order to make the PI Pallets ready for handling with a forklift, the space for forks needs to be defined during the next specification part. To create a maximum of output according to flexibility, PI Pallet will be designed as 4 Way-Pallet. 4-Way Pallets are defined as Pallets which can be handled by a forklift from all four sides [HPE17, p61].
Figure 52 shows the two basic design principles, combining the modular dimensions and the 4-way principle.

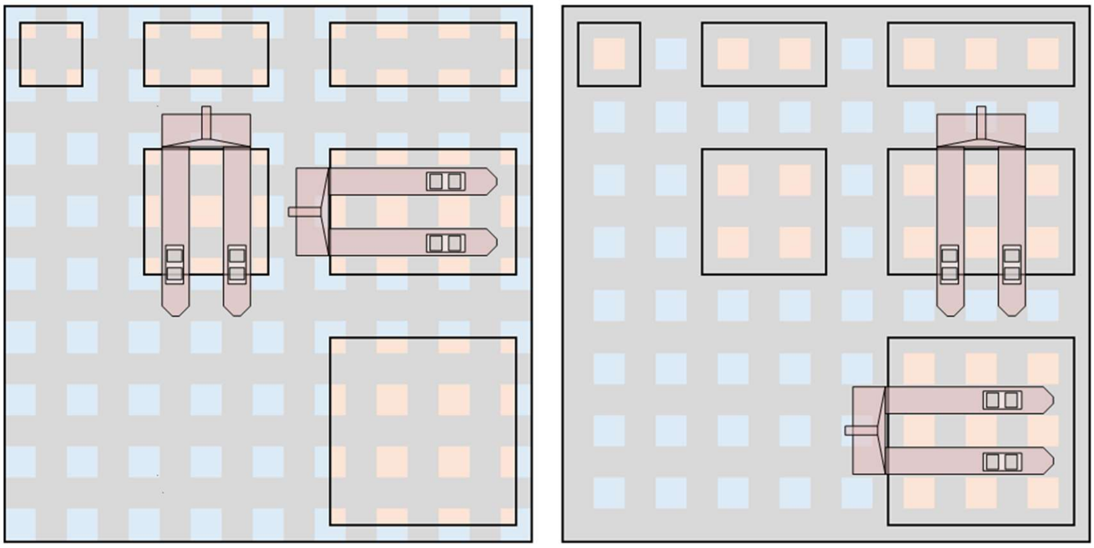


figure 52: 4-way design of PI Pallets

Due to instability when the PI Pallet is placed on the ground, and the disadvantages in potential conveyer transportation, the right design will not be considered within the following design steps. This means that the basic design will follow the left design principle, according to figure 52.
As shown, not every PI Pallet can be handled from all four sides as well as other variants because of the asymmetrical design and load situation. This disadvantage opposes the advantage of modularity in all directions of all PI Pallet variants. To minimise the effect of this disadvantage, the assumption is made that such situations of asymmetrical load and handling situations will be avoided by additional rules, constraints and safety installations during usage.

Combining all the considerations discussed in this chapter, the first rough design of the base parts in the six main dimensions was made. The outcome of this rough design is summed up in figure 53.

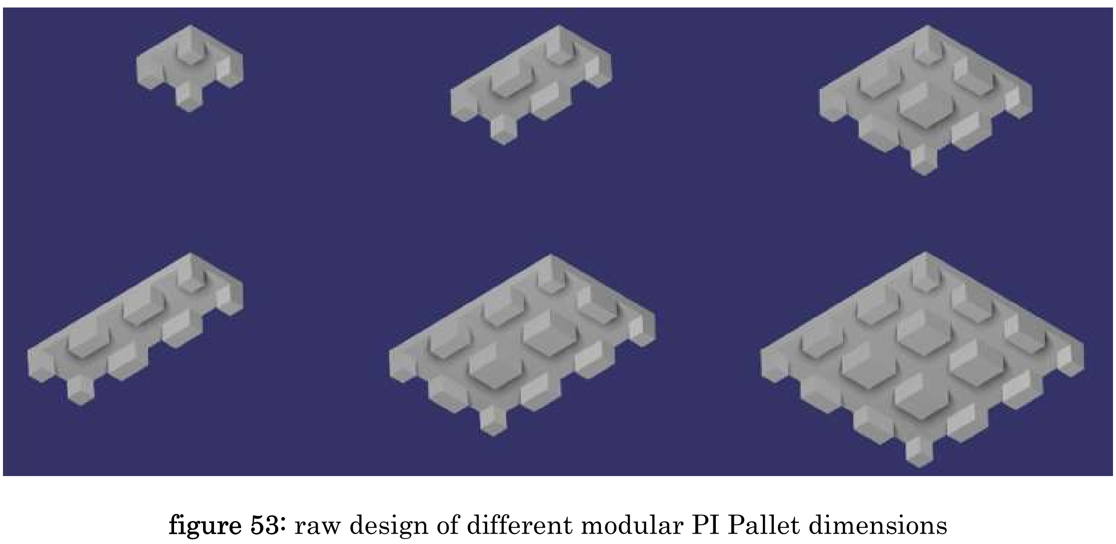


figure 53: raw design of different modular PI Pallet dimensions

After rough pre-designing of the base part of the PI Pallet following the main dimensions, the next step will be the pre-design of the inlay part of the PI Pallet.

4.3.3 Pre-design of the Inlay Part

As the inlay part is the decisive module due to interconnectivity between two or more PI Pallets to each other, this designs step mainly focusses on the definition of the function. This includes the pre-design of the connection mechanism.

In order to find out what the most effective and most suitable method to connect two or more PI Pallets to each other is, all possible ways to connect components will be listed. According to the categorization of the connecting process, this thesis uses a form of joining as a fitting procedure.
In DIN 8550, forming has been defined as the fourth main group of manufacturing technologies [DIN03a]. Figure 54 shows the classification of these manufacturing technologies into six main groups including the fourth main group of joining.

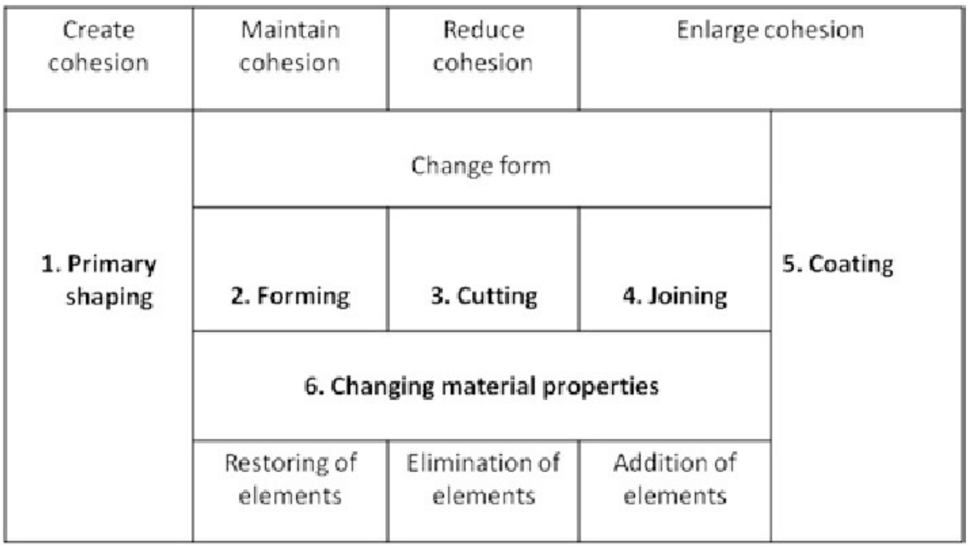


figure 54: Classification of manufacturing techniques according to DIN 8580-0 [DIN03a]

To find a suitable joining technology, the fourth main group of manufacturing techniques needs to be split up again in order to show all relevant state of the art joining methods. All joining methods according to DIN 8593-0 [DIN03a] to DIN 8593-8 [DIN03h] are categorized into subgroups, which are listed in figure 55. For further definition of the single joining technologies please note table 3.

joining techniques according to DIN 8593-0								
4.1 **assembling** DIN 8593-1	4.2 **filling** DIN 8593-2	4.3 **pressing** DIN 8593-3	4.4 **join by casting** DIN 8593-4	4.5 **join by forming** DIN 8593-5	4.6 **form by welding** DIN 8593-6	4.7 **form by soldering** DIN 8593-7	4.8 **adhesing** DIN 8593-8	4.9 **textile joining**
4.1.1 **stacking** DIN 8593-1	4.2.1 **infilling** DIN 8593-2	4.3.1 **screwing** DIN 8593-3	4.4.1 **moulding** DIN 8593-4	4.5.1 **wire forming** DIN 8593-5	4.6.1 **fusion welding** DIN 8593-6	4.7.1 **soft soldering** DIN 8593-7	4.8.1 **physical adhesing** DIN 8593-8	
4.1.2 **inserting** DIN 8593-1	4.2.2 **soaking** DIN 8593-2	4.3.2 **clamping** DIN 8593-3	4.4.2 **embedding** DIN 8593-4	4.5.2 **sheet metal forming** DIN 8593-5	4.6.2 **friction welding** DIN 8593-6	4.7.2 **brazing** DIN 8593-7	4.8.2 **chemical adhesing** DIN 8593-8	
4.1.3 **telescoping** DIN 8593-1		4.3.3 **clinching** DIN 8593-3	4.4.3 **potting** DIN 8593-4	4.5.3 **riveting** DIN 8593-5				
4.1.4 **hanging** DIN 8593-1		4.3.4 **inpressing** DIN 8593-3	4.4.4 **galvanizing** DIN 8593-4					
4.1.5 **locking** DIN 8593-1		4.3.5 **nailing** DIN 8593-3	4.4.5 **coating** DIN 8593-4					
4.1.6 **spreading** DIN 8593-1		4.3.6 **wedging** DIN 8593-3	4.4.6 **cementing** DIN 8593-4					
		4.3.7 **bracing** DIN 8593-3						

figure 55: joining methods according to DIN 8593-0 to DIN 8593-8 [DIN03a]-[DIN03h][1]

[1] As source for this picture, cited standards were used in German language and terms were translated by the author

table 3: definition of joining methods

joining method	definition
4.1.1 stacking	joining of fitting parts by usage principle of gravity for form fitting connection [DIN03b]
4.1.2 inserting	joining by laying a part inside a formfitting other part [DIN03b]
4.1.3 telescoping	joining by sliding one part over or in another part, whereas between the two parts a fit is formed [DIN03b]
4.1.4 hanging	joining by hanging one part in another part where as the joining force is defined by spring principle [DIN03b]
4.1.5 locking	joining by telescoping two parts whereas the joining process is a combination of a rotation and a translation movement [DIN03b]
4.1.6 spreading	joining by elastic forming and springing back of a part inside another part [DIN03b]
4.2.1 infilling	joining by filling liquid, gaseous or solid material into a hollow body [DIN03c]
4.2.2 soaking	joining by filling a porous body with a liquid material [DIN03c]
4.3.1 screwing	joining by the usage of self-locking threat [DIN03d]
4.3.2 clamping	joining by pressing parts to each other by usage of support parts, whereas the joined parts are getting deformed elastic or plastic while support parts stay rigid [DIN03c]
4.3.3 clinching	joining by pressing parts to each other by usage of elastic support parts [DIN03d]
4.3.4 inpressing	joining by pressing on part in another part whereas parts need to haven an over-size [DIN03d]
4.3.5 nailing	joining by pressing or hammer a nail as a support part into full material [DIN03d]
4.3.6 wedging	joining by usage of self-locking wedge-shaped support parts [DIN03d]
4.3.7 bracing	joining by usage of a conus or slit wedge whereas the required axial force is applied by a threat [DIN03d]
4.4.1 moulding	joining by casting in order to create an additional part out of formless material [DIN03e]
4.4.2 embedding	joining by casting in order to create an additional part out of formless material, whereas another part gets integrated [DIN03e]
4.4.3 potting	joining by usage of liquid material which gets solid later [DIN03e]
4.4.4 galvanizing	joining by galvanic connecting of support parts [DIN03e]
4.4.5 coating	joining by a casting a hull out of a formless material by using a forming tool [DIN03e]
4.4.6 cementing	joining of two different parts by usage of cement [DIN03e]
4.5.1 wire forming	joining of wires by forming parts of them [DIN03f]
4.5.2 sheet metal forming	joining of sheet metals forming by pressing them or change their form [DIN03f
4.5.3 riveting	joining by forming of bolt formed support part [DIN03f]
4.6.1 fusion welding	joining by welding by melting materials with heat source [DIN03g]
4.6.2 friction welding	joining by welding by melting materials with friction[DIN03g]
4.7.1 soft soldering	joining by soft soldering [DIN03h]
4.7.2 brazing	joining by brazing [DIN03h]
4.8.1 physical adhering	joining by sticking parts together by adhering with physical reaction [DIN03i]
4.8.2 chemical adhering	joining by sticking parts together by adhering with chemical reaction [DIN03i]

Due to specific properties and behaviour, not all the methods mentioned in table 3 and figure 55 are applicable to the procedure of connecting two or more PI Pallets to each other. To reduce this list of all joining technologies to a list of applicable joining methods, a list of K.O. criteria need to be defined in the next step. Each technique will be compared to these criteria. Only in case of passing all of them, the joining method is suitable and applicable for the tasks of interconnection between PI Pallets.

This list of K.O. criteria is set as followed:

a) Non-adhesive bonding:
The technique must not be based on an adhesive bonding mechanism. This indicates the usage of a method that is based on force locking, or form locking mechanisms.
b) Non-permanent:
The technique must not indicate a permanent connection between parts. The possibility to disconnect parts must be given.
c) Safe to operate:
The technique must provide a connection that can be hold securely. This includes the holding of connection, regardless of position and orientation of connected PI Pallets as well as environmental conditions.
d) Reusability:
The technique provides reusability during the lifespan of a PI Pallet. This indicates a non-destructive process of disconnection.

Applying this list of K.O. criteria to the possible joining techniques according to DIN 8593 lead to the result of nine techniques which are suitable for the task of connecting two or more PI Pallets to each other. Figure 56 shows the selection process of applying the K.O. criteria to the list of joining techniques.

K.O. criterias

✓ criteria fulfilled
× criteria not fulfilled

subgroup	A (not-adhesive bonding)	B (non-permanent)	C (safe to operate)	D (reusability)	comments	suitability
4.1.1	✓	✓	×		work principle by gravity	×
4.1.2	✓	✓	×		work principle by gravity	×
4.1.3	✓	✓	✓	✓		✓
4.1.4	✓	✓	✓	✓		✓
4.1.5	✓	✓	✓	✓		✓
4.1.6	✓	✓	✓	✓		✓
4.2.1	✓	✓	×		not safe to operate	×
4.2.2	×				adhesive, permanent	×
4.3.1	✓	✓	✓	✓		✓
4.3.2	✓	✓	✓	✓		✓
4.3.3	✓	✓	✓	✓		✓
4.3.4	✓	✓	✓	×	adhesive, permanent	×
4.3.5	✓	✓	✓	×	adhesive, permanent	×
4.3.6	✓	✓	✓	✓		✓
4.3.7	✓	✓	✓	✓		✓
4.4.1	×				adhesive, permanent	×
4.4.2	×				adhesive, permanent	×
4.4.3	×				adhesive, permanent	×
4.4.4	×				adhesive, permanent	×
4.4.5	×				adhesive, permanent	×
4.4.6	×				adhesive, permanent	×
4.5.1	✓	✓	✓	×	not multiple usable	×
4.5.2	✓	✓	✓	×	not multiple usable	×
4.5.3	✓	✓	✓	×	not multiple usable	×
4.6.1	×				adhesive, permanent	×
4.6.2	×				adhesive, permanent	×
4.7.1	×				adhesive, permanent	×
4.7.2	×				adhesive, permanent	×
4.8.1	×				adhesive, permanent	×
4.8.2	×				adhesive, permanent	×

figure 56: KO criteria applied on joining techniques

As shown in figure 56, the list of joining technologies has been limited to a list of nine relevant joining techniques based on applicability which is listed as follows:

- joining by telescoping
- joining by hanging
- joining by locking
- joining by spreading
- joining by screwing
- joining by clamping
- joining by clinching
- joining by wedging
- joining by bracing

These remaining joining technologies will be ranked, according to suitability and applicability to the task of connecting PI Pallet. For the basis for that ranking a multi-attribute utility analysis according to the description in chapter 3.1.5.1 is created.
To ensure an objective outcome, the first step is the definition of characteristics of every single joining technology.
Within the evaluation of joining technologies for the usage of connecting PI Pallets this list of characteristics is defined as follows:

- complexity
  is defined as the level of complexity the connection mechanism. This includes the number of different parts used and the manufacturability.
- scalability
  is defined as the readiness for easy expanding to any wished dimension by using additional material.
- required accuracy
  is defined as the range of tolerance required for the manufacturing of the single parts which are used for this mechanism as well as the range of tolerance required for the resulting mechanism at all.
- operation speed
  is defined as the time the operation process requires. This includes the timeframe for connecting two or more parts as well as the timeframe for disconnecting them.
- required loose parts
  is defined as the need for loose parts (e.g. screws, bolts, etc.) for fulfilling the task.
- required tools
  is defined as the need for tools in order to fulfil the task. This includes the connection process as well as the disconnection process.

- robustness
  is defined as the principal structure design of the whole mechanism. This includes the resistance against environmental conditions as well as the level of filigree of used parts.
- accessibility
  is defined as the need for access to the mechanism in order to fulfil the task. This includes the number of sides the mechanism should be accessible from, as well as the required space which is additionally needed in order to operate the mechanism.
- maintenance
  is defined as the amount of maintenance processes the mechanism requires during the lifespan. This includes the cleaning processes as well as repair and replacing processes because of wear and occurring failures.
- weight
  is defined as weight of the whole mechanism. This includes the weight of the mechanism itself as well as the weight of the potential additional parts needed for fulfilling the task.

Not all these characteristics have the same level of importance in the decision-making process. Because of the differences in these characteristics and the lack of comparability, a standardized method for their ranking based on the relevance for the decision-making process needs to be applied. The chosen method is pairwise comparison, according to the description in chapter 3.1.5.2

The decision, which characteristic is more important, is highly dependent on personal preferences. In order to create an objective outcome, the tables in figure 57 were created by four different people with different technical backgrounds (including the author of this thesis). The results have been anonymized for further analysis.

person 1		A	B	C	D	E	F	G	H	I	J	Σ	share
complexity	A		0	0	0	1	1	0	0	0	0	2	4,44%
scalability	B	1		1	0	1	1	0	1	0	1	6	13,33%
required accuracy	C	1	0		0	1	1	0	1	0	0	4	8,89%
operating speed	D	1	1	1		1	1	1	1	1	1	9	20,00%
required loose parts	E	0	0	0	0		1	0	0	1	0	2	4,44%
required tools	F	0	0	0	0	0		0	0	1	0	1	2,22%
robustness	G	1	1	1	0	1	1		1	0	0	6	13,33%
accessability	H	1	0	0	0	1	1	0		0	0	3	6,67%
maintainance	I	1	1	1	0	0	0	1	1		0	5	11,11%
weigth	J	1	0	1	0	1	1	1	1	1		7	15,56%

person 2		A	B	C	D	E	F	G	H	I	J	Σ	share
complexity	A		1	1	1	0	0	0	0	1	0	4	8,89%
scalability	B	0		0	1	1	1	0	0	0	0	3	6,67%
required accuracy	C	0	1		1	1	1	0	1	0	0	5	11,11%
operating speed	D	0	0	0		0	0	0	0	0	0	0	0,00%
required loose parts	E	1	0	0	1		1	1	1	0	0	5	11,11%
required tools	F	1	0	0	1	0		0	0	0	0	2	4,44%
robustness	G	1	1	1	1	0	1		1	0	0	6	13,33%
accessability	H	1	1	0	1	0	1	0		1	0	5	11,11%
maintainance	I	0	1	1	1	1	1	1	0		0	6	13,33%
weigth	J	1	1	1	1	1	1	1	1	1		9	20,00%

person 3		A	B	C	D	E	F	G	H	I	J	Σ	share
complexity	A		0	1	0	0	0	0	0	0	0	1	2,22%
scalability	B	1		1	0	1	1	1	1	1	1	8	17,78%
required accuracy	C	0	0		0	0	0	0	0	0	0	0	0,00%
operating speed	D	1	1	1		1	1	1	1	1	1	9	20,00%
required loose parts	E	1	0	1	0		0	0	0	1	1	4	8,89%
required tools	F	1	0	1	0	1		0	1	1	1	6	13,33%
robustness	G	1	0	1	0	1	1		1	1	1	7	15,56%
accessability	H	1	0	1	0	1	0	0		1	1	5	11,11%
maintainance	I	1	0	1	0	0	0	0	0		1	3	6,67%
weigth	J	1	0	1	0	0	0	0	0	0		2	4,44%

person 4		A	B	C	D	E	F	G	H	I	J	Σ	share
complexity	A		0	1	0	0	0	0	0	0	0	1	2,22%
scalability	B	1		1	1	1	1	1	1	1	1	9	20,00%
required accuracy	C	0	0		0	0	0	0	0	0	0	0	0,00%
operating speed	D	1	0	1		0	1	0	1	1	1	6	13,33%
required loose parts	E	1	0	1	1		1	0	1	1	1	7	15,56%
required tools	F	1	0	1	0	0		0	0	1	0	3	6,67%
robustness	G	1	0	1	1	1	1		1	1	1	8	17,78%
accessability	H	1	0	1	0	0	1	0		1	1	5	11,11%
maintainance	I	1	0	1	0	0	0	0	0		1	3	4,44%
weigth	J	1	0	1	0	0	1	0	0	1		4	8,89%

figure 57: pairwise comparison of characteristics

In next step, a definition of the key for the rating of every single characteristic of the different joining methods is created. This key should define a range from 1 (the characteristic is very badly represented) to 10 (perfect representation). In table 4, this rating key has been defined for every characteristic.

table 4: rating key for characteristics rating

	1 2 …	to	… 9 10
complexity	complex/many moving parts	to	simple/no moving
scalability	not scalable for modular dimensions	to	fully scalable for modular dimensions
required accuracy	tight tolance field required	to	wide tolance field required
operating speed	high disconnecting/connecting time	to	low connecting/disconnecting time
required loose parts	no spare parts required	to	many spare parts required
required tools	no tool required	to	special tool required
robustness	filigran	to	robust
accessability	no access reqired	to	allsided access required
maintainance	no maintainance required	to	high maintainance frequence required
weigth	low specific weigth	to	high specific weigth

Combining the outcomes from pairwise comparisons (see figure 57) as well as the rating key for the characteristics (see table 4) with a qualitative rating of the relevant joining technologies, the MAUA can be generated. This value of utility shows the sum of all quantitative ratings, defined by the qualitative rating combined with the rating key, multiplied by the weight of relevance. Figure 58figure 58 shows the qualitative rating as well as the relative rating and the value of weighted utility for each joining technology applied on every characteristic. Because of the appearance of different weighting tables (see figure 57), different values of weighted utility will be figured out, as well as a combination of them represented by the arithmetic average of these values. As a result of this table, the joining technologies have been ranked according to their values of weighted utility. Technologies ranked in 1 to 3 are marked within every category.

criteria	share [%] p1	p2	p3	p4
complexity	2,22%	2,22%	4,44%	8,89%
scalability	20,00%	17,78%	13,33%	6,67%
required accuracy	0,00%	0,00%	8,89%	11,11%
operating speed	13,33%	20,00%	20,00%	0,00%
required loose parts	15,56%	8,89%	4,44%	11,11%
required tools	6,67%	13,33%	2,22%	4,44%
robustness	17,78%	15,56%	13,33%	13,33%
accessability	11,11%	11,11%	6,67%	11,11%
maintainance	4,44%	6,67%	11,11%	13,33%
weigth	8,89%	4,44%	15,56%	20,00%

variant 4.1.3
telescoping

criteria	rating qualitative	quantitive	utility p1	p2	p3	p4	avg
complexity	few moving parts	6	0,13	0,13	0,27	0,53	0,27
scalability	easy scalable	8	1,60	1,42	1,07	0,53	1,16
required accuracy	tight tolerance range required	2	0,00	0,00	0,18	0,22	0,10
operating speed	fast operating time	8	1,07	1,60	1,60	0,00	1,07
required loose parts	litte loose parts required	6	0,93	0,53	0,27	0,67	0,60
required tools	no tool required	10	0,67	1,33	0,22	0,44	0,67
robustness	very robust	9	1,60	1,40	1,20	1,20	1,35
accessability	one side accessabilty required	7	0,78	0,78	0,47	0,78	0,70
maintainance	moderate to high wearing rate	4	0,18	0,27	0,44	0,53	0,36
weigth	tendence to high weight	4	0,36	0,18	0,62	0,80	0,49
		weighted utility	7,31	7,64	6,33	5,71	6,75
		ranking	1	1	1	8	1

variant 4.1.4
hanging

criteria	rating qualitative	quantitive	utility p1	p2	p3	p4	avg
complexity	no moving parts	10	0,22	0,22	0,44	0,89	0,44
scalability	easy scalable by additional loose parts	7	1,40	1,24	0,93	0,47	1,01
required accuracy	very wide tolerance range required	10	0,00	0,00	0,89	1,11	0,50
operating speed	moderate operating time	5	0,67	1,00	1,00	0,00	0,67
required loose parts	few looseparts rewuired	4	0,62	0,36	0,18	0,44	0,40
required tools	no tool required	10	0,67	1,33	0,22	0,44	0,67
robustness	moderate robustness	5	0,89	0,78	0,67	0,67	0,75
accessability	all side accesability required	2	0,22	0,22	0,13	0,22	0,20
maintainance	moderate wearing rate	6	0,27	0,40	0,67	0,80	0,53
weigth	tendence to low weight	6	0,53	0,27	0,93	1,20	0,73
		weighted utility	5,49	5,82	6,07	6,24	5,91
		ranking	7	5	2	2	4

variant 4.1.5
einrenken

criteria	rating qualitative	quantitive	utility p1	p2	p3	p4	avg
complexity	many moving parts	3	0,07	0,07	0,13	0,27	0,13
scalability	moderate scalable	5	1,00	0,89	0,67	0,33	0,44
required accuracy	tight tolerance range required	2	0,00	0,00	0,18	0,22	0,18
operating speed	fast operating time	10	1,33	2,00	2,00	0,00	0,89
required loose parts	no spare parts required	10	1,56	0,89	0,44	1,11	0,89
required tools	no tool required	10	0,67	1,33	0,22	0,44	0,89
robustness	high robustness	10	1,78	1,56	1,33	1,33	0,89
accessability	design dependent	5	0,56	0,56	0,33	0,56	0,44
maintainance	high wearing rate	2	0,09	0,13	0,22	0,27	0,18
weigth	high weight	2	0,18	0,09	0,31	0,40	0,18
		weighted utility	7,22	7,51	5,84	4,93	5,11
		ranking	2	2	5	9	9

criteria	share [%] p1	p2	p3	p4
complexity	2,22%	2,22%	4,44%	8,89%
scalability	20,00%	17,78%	13,33%	6,67%
required accuracy	0,00%	0,00%	8,89%	11,11%
operating speed	13,33%	20,00%	20,00%	0,00%
required loose parts	15,56%	8,89%	4,44%	11,11%
required tools	6,67%	13,33%	2,22%	4,44%
robustness	17,78%	15,56%	13,33%	13,33%
accessability	11,11%	11,11%	6,67%	11,11%
maintainance	4,44%	6,67%	11,11%	13,33%
weigth	8,89%	4,44%	15,56%	20,00%

variant 4.1.6
spreading

criteria	rating qualitative	quantitive	utility p1	p2	p3	p4	avg
complexity	no moving parts	10	0,22	0,22	0,44	0,89	0,44
scalability	easy scalable	8	1,42	1,42	1,07	0,53	1,11
required accuracy	very tight tolerance range required	1	0,00	0,00	0,09	0,11	0,05
operating speed	fast connecting time, moderate disconect time	3	0,60	0,60	0,60	0,00	0,45
required loose parts	no loose parts required	10	0,89	0,89	0,44	1,11	0,83
required tools	no tool required	10	1,33	1,33	0,22	0,44	0,83
robustness	moderat robustness, continous bending	4	0,62	0,62	0,53	0,53	0,58
accessability	no accessability required	9	1,00	1,00	0,60	1,00	0,90
maintainance	high wearing rate	3	0,20	0,20	0,33	0,40	0,28
weigth	tendence to high weight	4	0,18	0,18	0,62	0,80	0,44
		weighted utility	6,47	6,47	4,96	5,82	5,93
		ranking	3	3	9	6	3

variant 4.3.1
screwing

criteria	rating qualitative	quantitive	utility p1	p2	p3	p4	avg
complexity	no moving parts	10	0,22	0,22	0,44	0,89	0,44
scalability	scalable by additional screws	7	1,24	1,24	0,93	0,47	0,97
required accuracy	tight tolerance range required	3	0,00	0,00	0,27	0,33	0,15
operating speed	very slow operating time	2	0,40	0,40	0,40	0,00	0,30
required loose parts	few loose parts required	4	0,36	0,36	0,18	0,44	0,33
required tools	standard tool required	4	0,53	0,53	0,09	0,18	0,33
robustness	very robust	10	1,56	1,56	1,33	1,33	1,44
accessability	two side access required	5	0,56	0,56	0,33	0,56	0,50
maintainance	low wearing rate	9	0,60	0,60	1,00	1,20	0,85
weigth	tendence to high weight	4	0,18	0,18	0,62	0,80	0,44
		weighted utility	5,64	5,64	5,60	6,20	5,77
		ranking	6	6	7	3	6

variant 4.3.2
clamping

criteria	rating qualitative	quantitive	utility p1	p2	p3	p4	avg
complexity	no moving parts	10	0,22	0,22	0,44	0,89	0,44
scalability	scalable by additional clamps	6	1,20	1,07	0,80	0,40	0,87
required accuracy	moderate tolenance range required	5	0,00	0,00	0,44	0,56	0,25
operating speed	slow operating time	3	0,40	0,60	0,60	0,00	0,40
required loose parts	few loose parts required	4	0,62	0,36	0,18	0,44	0,40
required tools	standard tool required	4	0,27	0,53	0,09	0,18	0,27
robustness	low robustness	4	0,71	0,62	0,53	0,53	0,60
accessability	one side accessability required	7	0,78	0,78	0,47	0,78	0,70
maintainance	high wearing rate	3	0,13	0,20	0,33	0,40	0,27
weigth	low weight	8	0,71	0,36	1,24	1,60	0,98
		weighted utility	5,04	4,73	5,13	5,78	5,17
		ranking	8	8	8	7	8

criteria	share [%] p1	p2	p3	p4
complexity	2,22%	2,22%	4,44%	8,89%
scalability	20,00%	17,78%	13,33%	6,67%
required accuracy	0,00%	0,00%	8,89%	11,11%
operating speed	13,33%	20,00%	20,00%	0,00%
required loose parts	15,56%	8,89%	4,44%	11,11%
required tools	6,67%	13,33%	2,22%	4,44%
robustness	17,78%	15,56%	13,33%	13,33%
accessability	11,11%	11,11%	6,67%	11,11%
maintainance	4,44%	6,67%	11,11%	13,33%
weigth	8,89%	4,44%	15,56%	20,00%

variant 4.3.3
chiching

criteria	rating qualitative	quantitive	utility p1	p2	p3	p4	avg
complexity	no moving parts	10	0,22	0,22	0,44	0,89	0,44
scalability	scalable by additional clinches	7	1,40	1,24	0,93	0,47	1,01
required accuracy	wide tolerance range required	8	0,00	0,00	0,71	0,89	0,40
operating speed	slow operating time	3	0,40	0,60	0,60	0,00	0,40
required loose parts	many loose parts required	3	0,47	0,27	0,13	0,33	0,30
required tools	special tool requird	2	0,13	0,27	0,04	0,09	0,13
robustness	moderat to high robustness	6	1,07	0,93	0,80	0,80	0,90
accessability	all side accessability required	2	0,22	0,22	0,13	0,22	0,20
maintainance	low wearing rate	9	0,40	0,60	1,00	1,20	0,80
weigth	moderate to low weight	6	0,53	0,27	0,93	1,20	0,73
		weighted utility	4,84	4,62	5,73	6,09	5,32
		ranking	9	9	6	4	7

variant 4.3.6
wedging

criteria	rating qualitative	quantitive	utility p1	p2	p3	p4	avg
complexity	no moving parts	10	0,22	0,22	0,44	0,89	0,44
scalability	scalable by additional wegdes	7	1,40	1,24	0,93	0,47	1,01
required accuracy	moderate tolerance range required	5	0,00	0,00	0,44	0,56	0,25
operating speed	moderate operating time	5	0,67	1,00	1,00	0,00	0,67
required loose parts	few loose parts required	5	0,78	0,44	0,22	0,56	0,50
required tools	special tool required	2	0,13	0,27	0,04	0,09	0,13
robustness	moderat to high robustness	6	1,07	0,93	0,80	0,80	0,90
accessability	one side accessability requested	7	0,78	0,78	0,47	0,78	0,70
maintainance	moderate wearing rate	5	0,22	0,33	0,56	0,67	0,44
weigth	moderate to low weight	6	0,53	0,27	0,93	1,20	0,73
		weighted utility	5,80	5,49	5,84	6,00	5,78
		ranking	5	7	4	5	5

variant 4.3.7
bracing

criteria	rating qualitative	quantitive	utility p1	p2	p3	p4	avg
complexity	no moving parts	10	0,22	0,22	0,44	0,89	0,44
scalability	easy scalable by additional screws	7	1,40	1,24	0,93	0,47	1,01
required accuracy	tight tolerance range required	3	0,00	0,00	0,27	0,33	0,15
operating speed	very slow operating time	2	0,27	0,40	0,40	0,00	0,27
required loose parts	few loose parts required	4	0,62	0,36	0,18	0,44	0,40
required tools	standard tool required	4	0,27	0,53	0,09	0,18	0,27
robustness	very robust	10	1,78	1,56	1,33	1,33	1,50
accessability	one side accessability required	7	0,78	0,78	0,47	0,78	0,70
maintainance	low wearing rate	9	0,40	0,60	1,00	1,20	0,80
weigth	moderate weight	5	0,44	0,22	0,78	1,00	0,61
		weigthed utility	6,18	5,91	5,89	6,62	6,15
		ranking	4	4	3	1	2

figure 58: multi-attribute utility analysis

Based on the outcomes of the multi-attribute utility analysis (see figure 58), the decision was made to focus on telescoping as the mechanism used for connecting PI Pallets.
As mentioned before, the technique is defined as a process which includes an outer part and an inner part that are telescoped to each other (see table 3). The special feature of the following pre-design of that mechanism is the use of hooks, which leads to the usage as the inner or outer part in one. This allows the applicability of the same mechanism on both PI Pallets which need to be connected. Furthermore, this usage of hooks solves the male-female dilemma by the applicability for both directions in the same way.
Figure 59 shows the working principle of this pre-design by telescoping hooks to each other in two different variants, regardless of the source of movement.

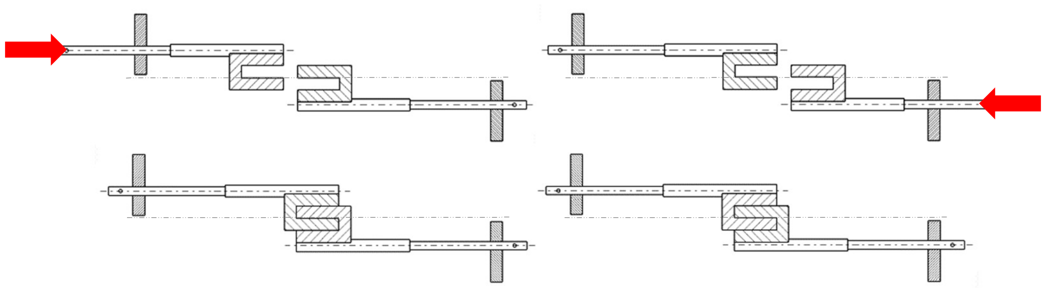


figure 59: work principle interconnection mechanism

This principle can easily be scaled up to all occurring dimensions of PI Pallets (see chapter 4.3.2). Due to the selection process in the pre-design of the base part, the relevant dimensions will be 400mm, 800mm and 1200mm. By applying these three dimensions to the mechanism's pre-design, the following three different dimensions of the mechanism can be outlined:

- Long: for PI Pallet of length and/or width of 1200mm
- Medium: for PI Pallet of length and/or width of 800mm
- Short: for PI Pallet of length and/or width of 400mm

Figure 60 shows these three versions of the connecting mechanism's pre-design

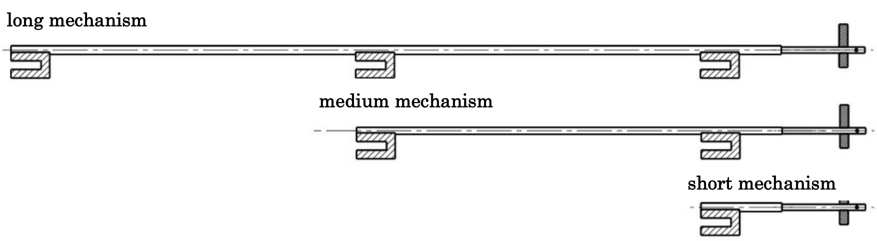


figure 60: dimensions of connection mechanism

4.3.4 Pre-design of the Top Part

After finishing the pre-design of the base part (see chapter 4.3.2) and the inlay part (see chapter 4.3.3), the last pre-designed module will be the top part of the PI Pallet.
As the primary function of the top part is the interconnectivity to the PI Container in any shape and dimension, the pre-design will focus on that feature. For simplifying this pre-design process step, the assumption is made that the used technology of connected PI Container is based on MODULUSHCA design (see chapter 2.2.4). Further, the constraint is set that the design of the top part will not include an active connection mechanism and the connection will be processed by the MODULUSHCA mechanism.
In order to create a MODULSHCA compatible top part with a compatible pattern, the existing pattern of connection elements from PI Containers is transferred to the top part. Figure 61 shows the basic pattern dimensions of MODULUSHCA technology used in PI Container.

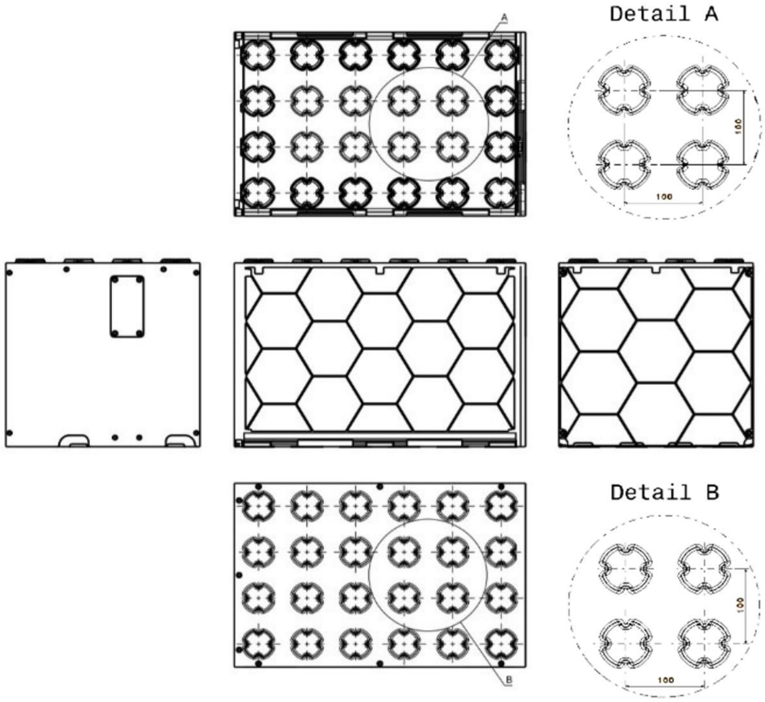


figure 61: MODULUSHCA dimensions and pattern

This basic pattern can be transferred directly to the pre-design of the top part. This thesis does not address the analysis of the exact geometry of the connection elements. For the design step of the top part, the geometry has been implemented directly from CAD files of the MODULUHCA project. According to the different used PI Pallet dimensions, figure 62 shows all possible forms and variants of the top parts used for different PI Pallets, including the MODULUSHCA connection elements.

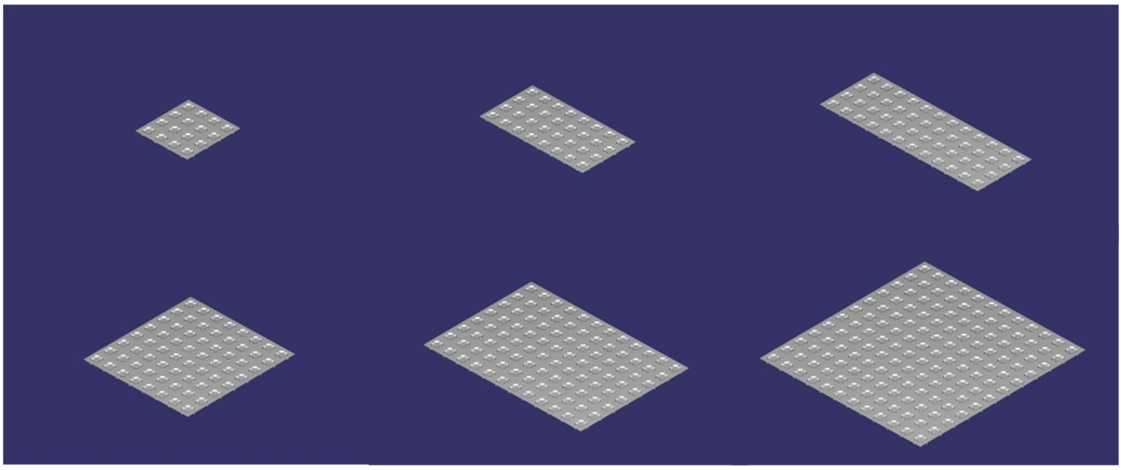


figure 62: pre-design of top part in different dimensions

After the pre-designing of the base, inlay and top part, the boundary conditions, basic dimensions, rough design and principal functions have been defined. These specifications are used as a basis for the next design step, according to VDI 2221, the design of the entire final product.

4.4 Conclusive Design of a PI Pallet

In this stage of methodical design, the PI Pallet is finalized by the conclusive design. The basis for this step is the outcome from the previous chapter 4.3. The combination of the modules which will lead to the end design, will be executed in this chapter. Please note that in this thesis, only the end result of the whole design process is presented. This does not include the description of the iteration steps necessary because of cross-relations between the modules.

4.4.1 Final Design of the Base Part

According to all the specification defined in the previous chapters and following the rough pre-design taken in chapter 4.3.2, the final design of the base part has been defined. In order to be able to reach all potential design variants, the material selection of the modules was not an explicit part of this thesis. This also excludes the selection of the manufacturing method. Due to that, the design was taken in a way which allows to be easily adapted to the requirements of any state-of-the-art manufacturing method, e.g. moulding, milling, welding or 3D-printing. Due to the occurring variants of PI Pallets, all relevant variants of the base part were designed in detail. The design of the base parts of all dimensions are summed up in figure 63.

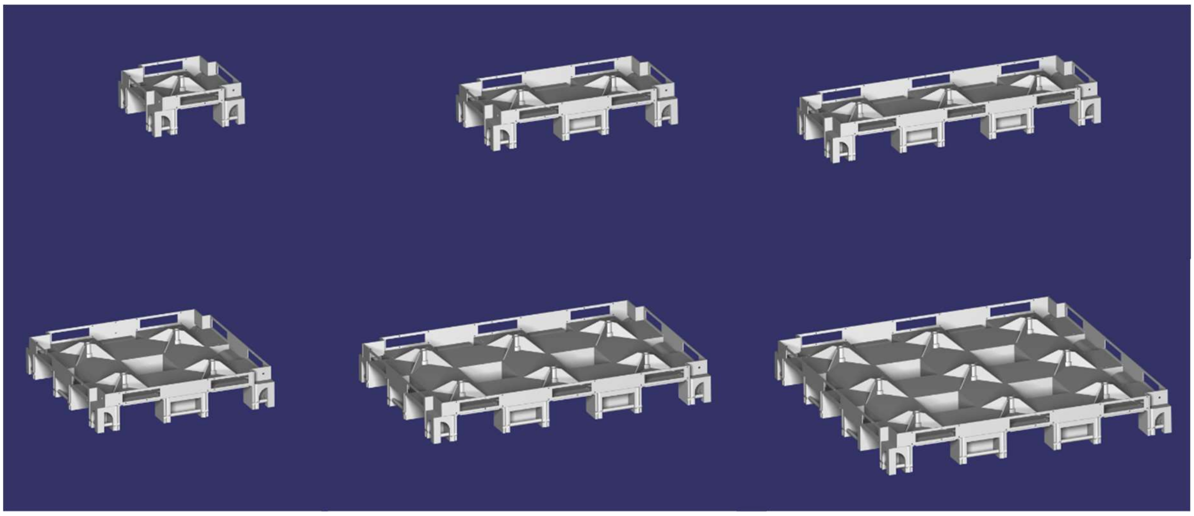


figure 63: final design of the base part in different dimensions

In order to depict the details of the design, one of the variants (1200mm x 800mm) is described in detail as an example. The design elements shown in figure 64 are identical for all variants, only the dimensions differ from the explained variant.

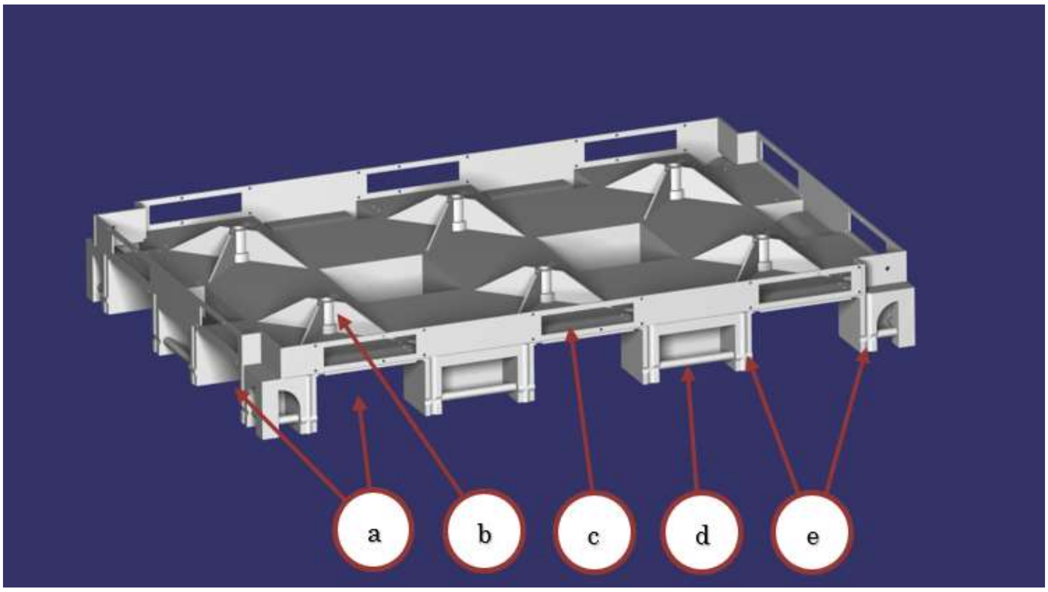


figure 64: final design base part 1200x800 details

a) 4-Way Entry for Standard Forklift Dimensions
   Following the pre-design of the base part (see chapter 4.3.2), this final design includes an entry for a standard forklift from all four sides.

b) Connector Element for the Top Part
   In order to hold the top part, there are connection elements placed on the top of the base part. Screws from underneath will additionally secure the top part.

c) Connector Element for the Inlay Part
In order to hold the inlay parts, there are connection elements placed on the four sides of the base part. The inlay parts will be mounted to the inside of the base part and will be secured by screws from outside.

d) Transport Locking Elements
In order to secure the PI Pallet during transportation, transport locking elements are located on each side of the base part. These elements allow locking to the transport device using hooks or belts.

e) Positioning Elements
In order to position two or more PI Pallets relative to each other, form-locking positioning elements were added at all four sides of the base part. Compared to active positioning elements (e.g. by using screws or similar), these passive elements have the advantage of no needed additional effort or energy and a short positioning time. In order to enable the usage of these form-locking elements on all sides in all possible positions of the base part, a combination of male and female geometry has been used, which can exemplarily be seen in figure 65. This combination of male and female geometry follows the Poka Yoke principle. [2]

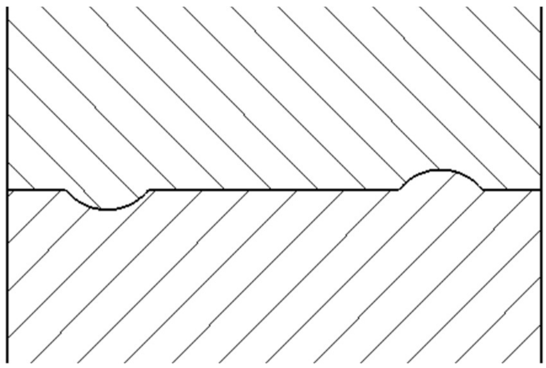


figure 65: passive positioning system by positive-negative-geometry elements

[2] Wikipedia: "Poka-yoke (ポカヨケ, [poka yoke]) is a Japanese term that means "mistake-proofing" or "inadvertent errorprevention". A poka-yoke is any mechanism in any process that helps an equipment operator avoid (yokeru) mistakes (poka). Its purpose is to eliminate product defects by preventing, correcting, or drawing attention to human errors as they occur."

4.4.2 Final Design of the Inlay Part

The second module, the final design of which will be described in detail in this chapter, is the inlay part. According to the pre-design (see chapter 4.3.3) and the three different main dimensions, three versions of the inlay part were designed. Figure 66 shows the front view as well as the back view of all designed variants with dimensions of short (right), medium (middle) and long (right).

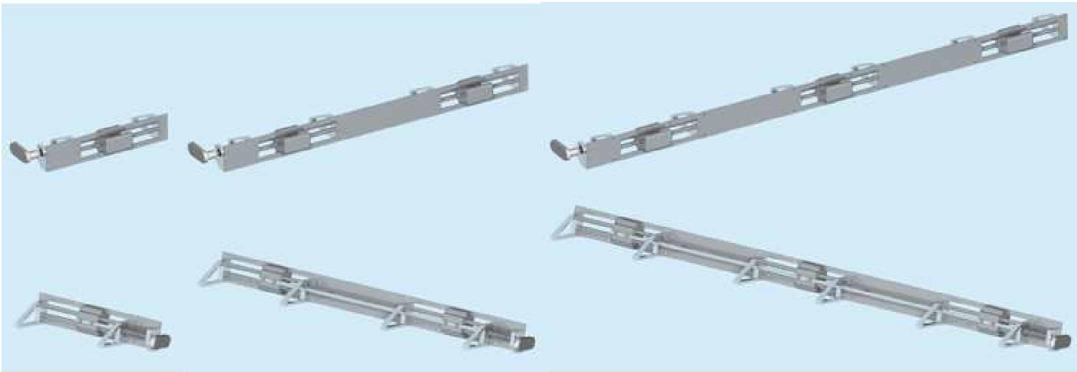


figure 66: final design of the inlay part in different variants

In order to outline the details of the design, one of these three variants (medium) is exemplarily described in detail. The design elements shown in figure 67 are identical for all variants, only the dimensions differ from the explained variant.

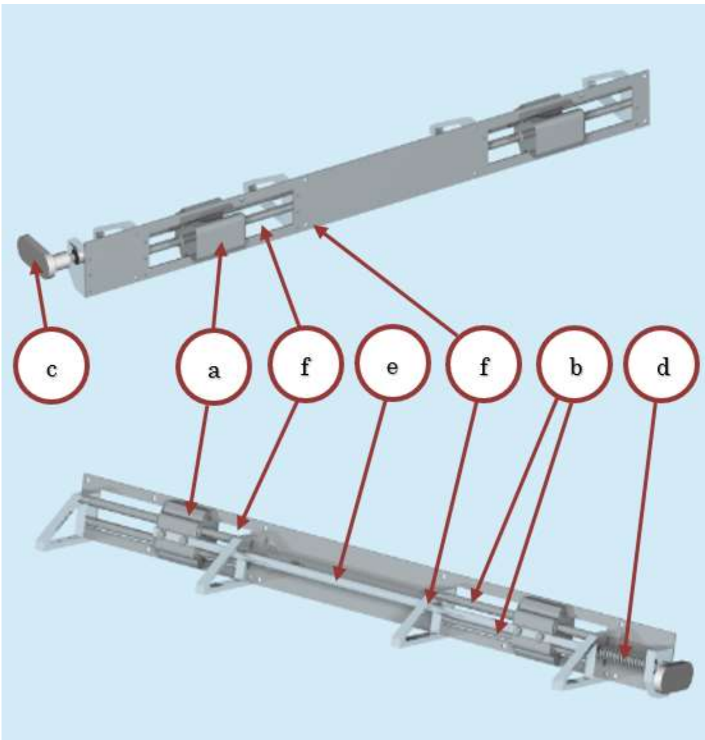


figure 67: final design of the inlay part (medium) in detail

a) Connection Hook

As explained in chapter 4.3.3, the main parts of the connection mechanism are the connection hooks, which will be telescoped into each other. These hooks are sliding on the guide rails supported by slide bearing. The design, which can be seen in figure 68, is based on the expected power flow within the hook during connection and its optimal distribution in the hook. The hook is connected via a spacer to the trigger which moves the hook.

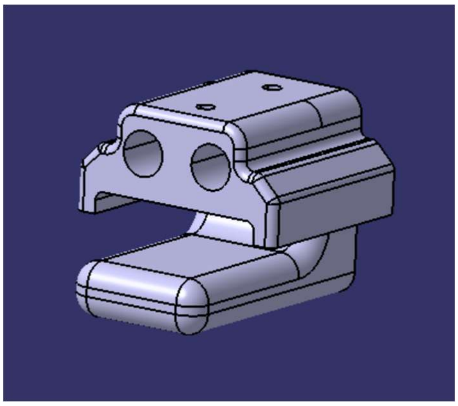


figure 68: connection hook

b) Guide Rail

The hook is sliding via the slide bearing on the mounted guide rails. The design of the guide rail is presented by two parallel cylindrical rails. This enables a stable movement of the hook during the connection and disconnection process.

c) Trigger

The trigger will apply the energy, force and movement during the connecting and disconnection process. The design of this trigger allows the application of extern energy, manual or by an automated device. This system has the advantage, compared to an internal energy source that is located on the pallet, of a no required electrical elements located on the PI Pallet, which was defined as a requirement in chapter 4.1.2.

d) Pull-Back Spring

In order to hold a connection without the need for external energy, a spiral spring has been implemented in this mechanism. The spring forces a back moving of the hooks to the initial position when a connection is applied as well as in situations without connection to other PI Pallets. The usage of one single spring implements the same trigger force for all mechanism variants.

e) Spacer

The hooks are connected to the trigger via a spacer, which enables the transfer of movement and force from the trigger to the hook. Furthermore, the spacer guarantees a constant distance between the hooks, as well as the synchronic movement of the hooks during the connection and disconnection process. The spacer is connected to the hooks by screws and to the trigger via a fastening pin.

f) Recess

The rectangular holes in the mounting sheet metal are necessary for allowing the movement of the hook as well as the insertion of the hook of the counterpart PI Pallet, and its movement.

g) Connection to the Base Part

The inlay part will be connected to the base part by the usage of additional anchor sheet metals and screws. The support structure stabilizes the mechanism during the usage of the connection mechanism and enables an optimal force distribution.

4.4.3 Final Design of the Top Part

The last partial final design addresses the top part. As mentioned previously, the design highly depends on the interconnection mechanism of the PI Container, which will be connected to the PI Pallet. In this thesis, the technology of MODULUSHCA has been used as a basis. The top part, as well as the connector to the base part, are made that the used top part can be easily replaced with another top part, which is suitable for another PI Container technology. This thesis does explicitly sketch out the design of a MODULUSCA compatible top part and does not address potential top parts compatible with other PI Containers. This design step results in the differently dimensioned variants of the top part shown in figure 69.

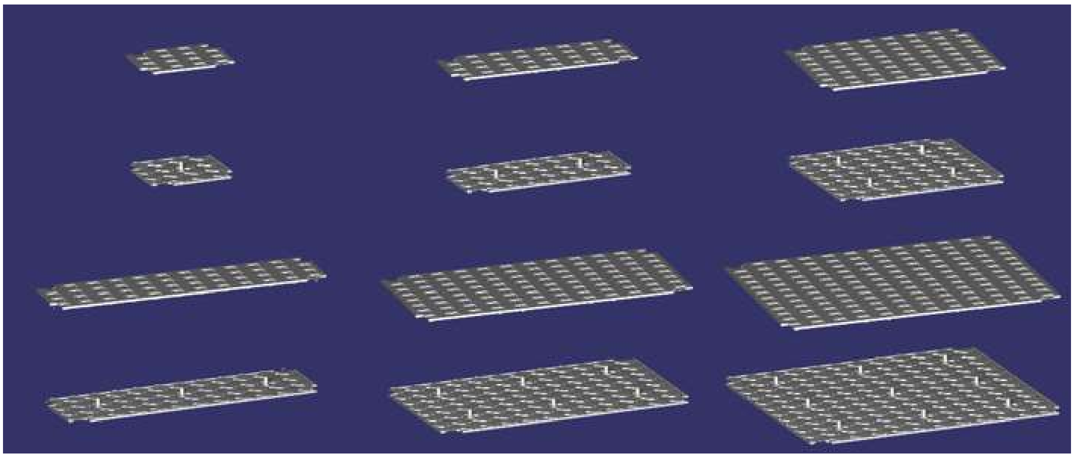


figure 69: final design of the top part in different variants

In order to sketch some the details of the design, one of these six variants (1200mm x 80mm) is exemplarily described in detail. The design elements shown in figure 70 are identical for all variants, only the dimensions do differ from the explained variant.

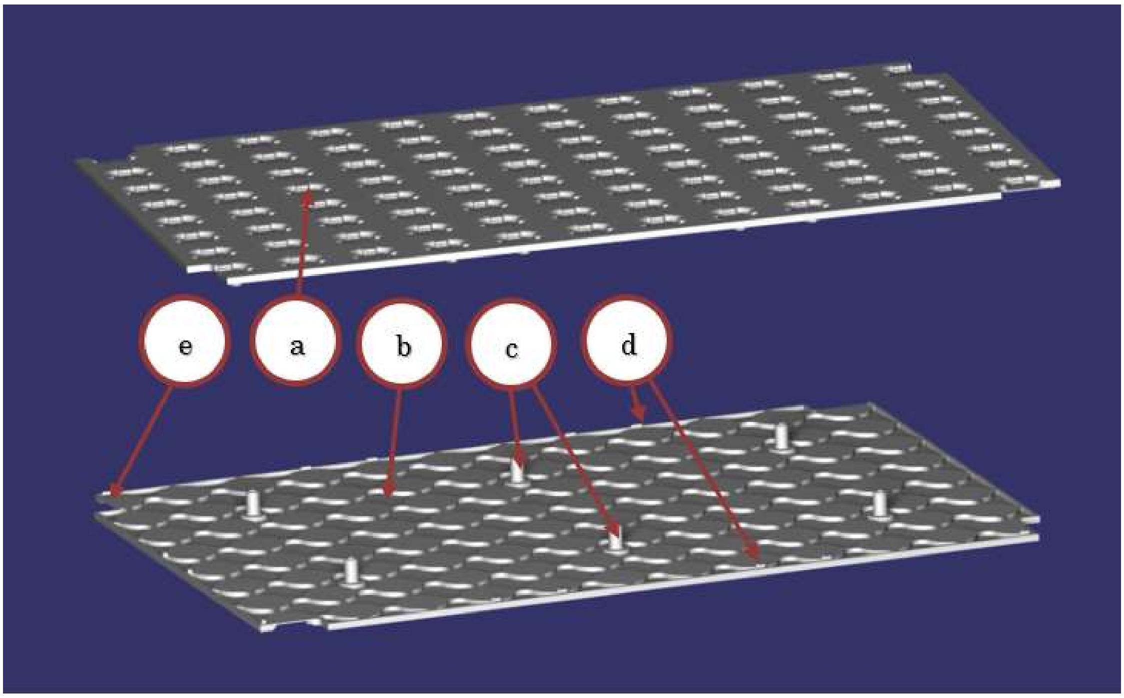


figure 70: final design of the top part 1200mm x 800mm in detail

a) MODULUSHCA Connection Pattern

As explained before, the basic principle to connect PI Containers to the top part is the connecting mechanism included in the PI Container. When using MODULUSHCA, the female geometry pattern of the connectors from the MODULUSHCA-Container is placed on the top part. This basic geometry can be seen in figure 71.

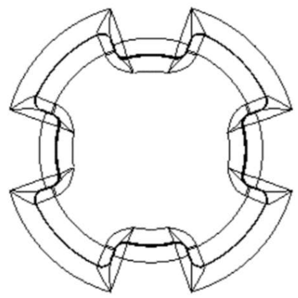


figure 71: MODULUSHCA locking geometry

b) Lightweight structure

In order to fulfil the requirement of lightweight, the structure on the lower side of the PI Pallet allows to save material which implicates the reduction of weight, whereas the structural strength stays nearly the same. The basic geometry and structure can be seen in figure 72.

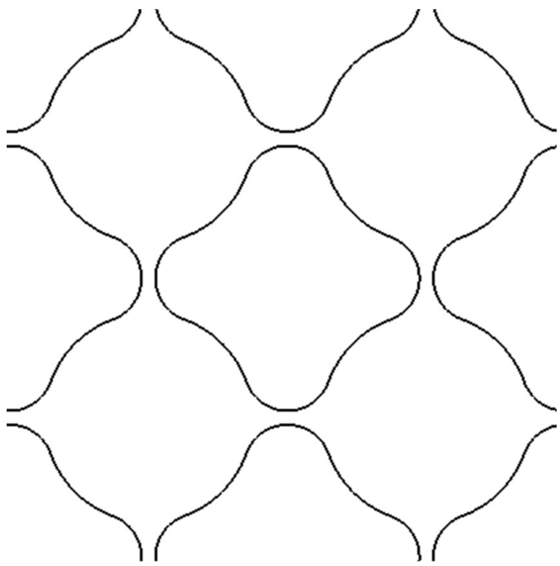


figure 72: light weight structure

c) Connection Pins

In order to position and connect the top part to the base part, connection pins are placed on the bottom of the top part. The connection is ensured via screws from underneath.

d) Position Elements

Additional to the connection pins, position elements were placed on the bottom of the top part. These elements allow the easy and fast positioning and adjustment of the top part relative to base part. The position elements can be seen in figure 73.

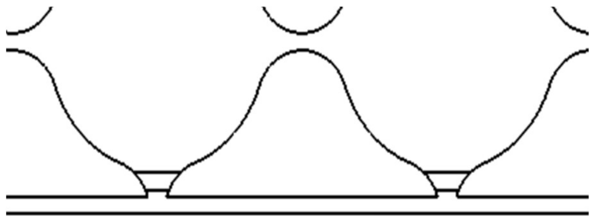


figure 73: position elements

4.4.4 Final Overall Design of the PI Pallet

The combination of the design variants of the base part, inlay part and top part (chapters 4.4.1 to 4.4.3) results in the final design of the PI Pallet. Based on the different variants of the modules, six different design variants of the resulting PI Pallet can be set, which are shown in figure 74.

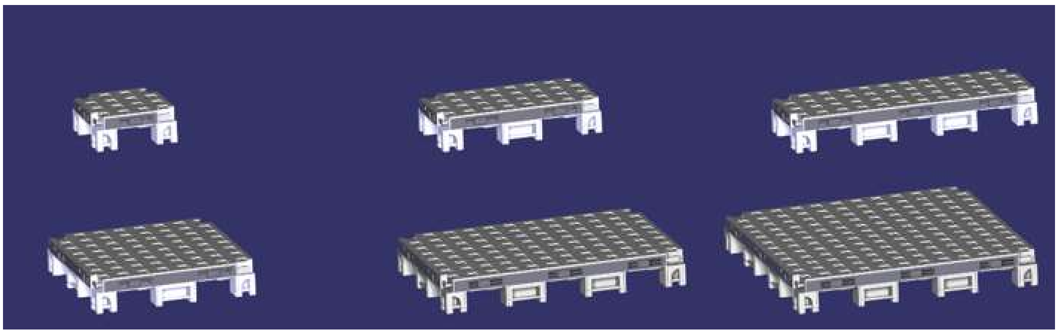


figure 74: final design of the PI Pallet in different variants

As shown before with modules, the details of the PI Pallet's final design are sketched exemplarily on the variant with dimensions of 1200mm x 800mm. The design elements shown in figure 75 are identical for all variants, only the dimensions differ from the explained variant. As the single modules were already described in chapter 4.4.1 to 4.4.3, this description shows the connection between the modules.

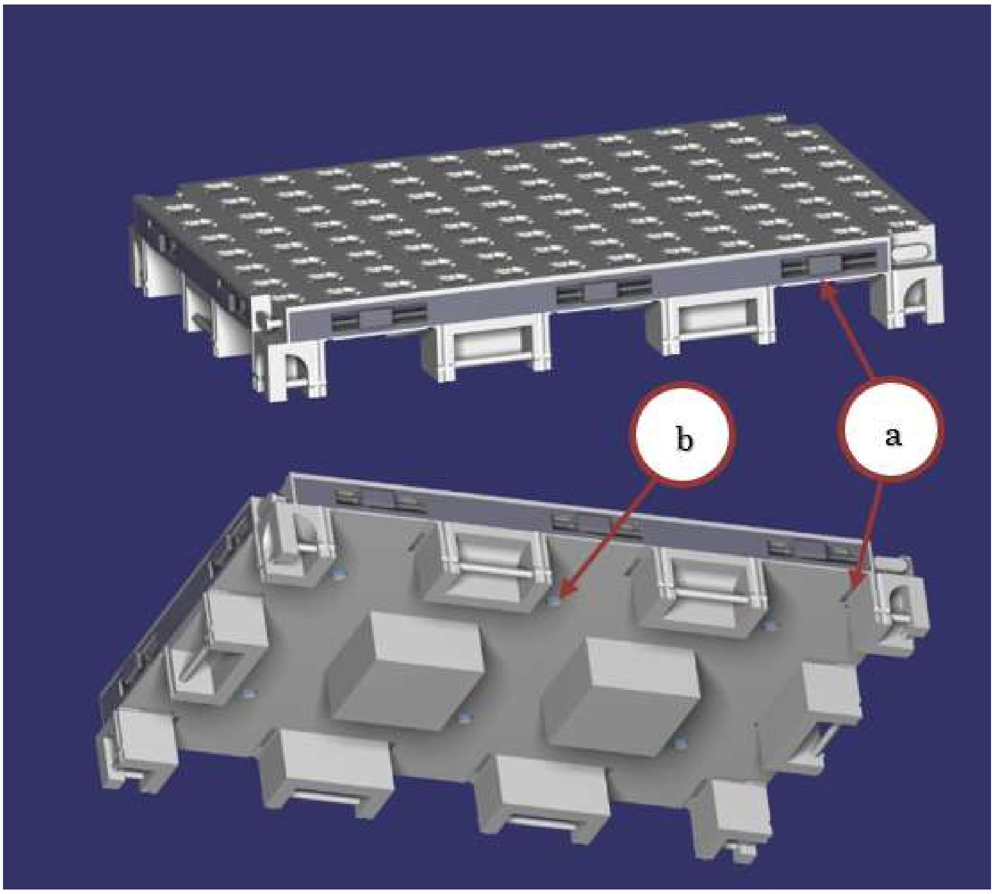


figure 75: final design of the PI Pallet 1200x800 in detail

a) Connection between Base Part and Inlay Part

The four inlay parts will be mounted on the base part via screws from the outside and from underneath. In order to distribute the force to the structure of the base part, additional sheet metals are used as an anchor. The position of the anchor sheet metal, as well as the inlay part, is defined by the connector for the inlay part on the base part (see chapter 4.4.1).

a) Connection between Base Part and Top Part

The top part will be mounted on the base part via screws from underneath. The positioning and orientation of the top part is defined by the position of the connection pins and the positioning elements on the top part (see chapter 4.4.3)

5 Analysis

This chapter analyses and evaluates the final design of the PI Pallet system, in the form of a listed SWOT analysis. As described in chapter 3.2, this includes the listing of strengths and weaknesses addressing aspects concerning the PI Pallet as a product itself, as well as opportunities and threats, addressing aspects concerning the usage of PI Pallet in potential PI scenarios.

5.1 Strengths

The strengths of the final design do address the features according to interconnectivity between two or more PI Pallets as well as the capacity to hold a static load.

Operability of Forming PI Pallet Units

The main strength of the PI Pallet is the interconnectivity between two or more PI Pallets. PI Pallets can be connected easily and quickly by pulling the trigger of the inlay part, without the use of any tools or loose parts. The combination of the integrated spring in the mechanism and the position elements on the base part provides a safe connection. The disconnection process can be operated the same way. The mechanism of the inlay part is designed in a way that requires only the activation of one of the connected PI Pallet. This allows forming PI Pallet Units of almost every shape of the consisting Single PI Pallets. Figure 76 exemplarily shows a PI Pallet Unit formed out of three different Single PI Pallet variants.

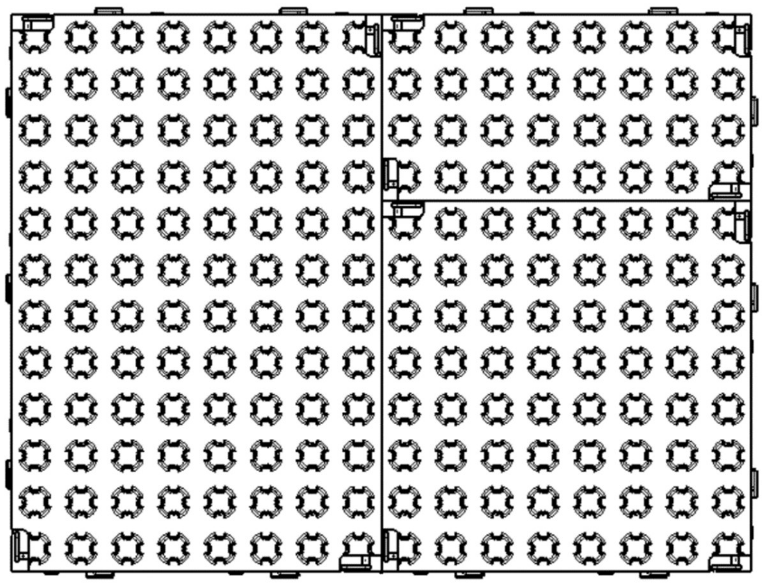


figure 76: PI Pallet Unit

Load
According to the requirements set in chapter 4.1.2, the PI Pallet was designed to hold a 4.000kg static load. The assumption was made that this specification was made for the PI Pallet of size 1200mm x 800mm, which are the same dimensions as of standard EURO Pallets [HK15, p135]. To clarify if the PI Pallet can hold the static load of 4.000 kg, this load situation has been simulated. The used method of simulation was an FE based topology optimizing algorithm, which shows that the geometry of the PI Pallet as it was designed is sufficient to bear the maximum of an estimated load. For simulation, the assumption was made that the base part is made of a state-of-the-art plastic material. Figure 77 presents the outcome of that simulation process.

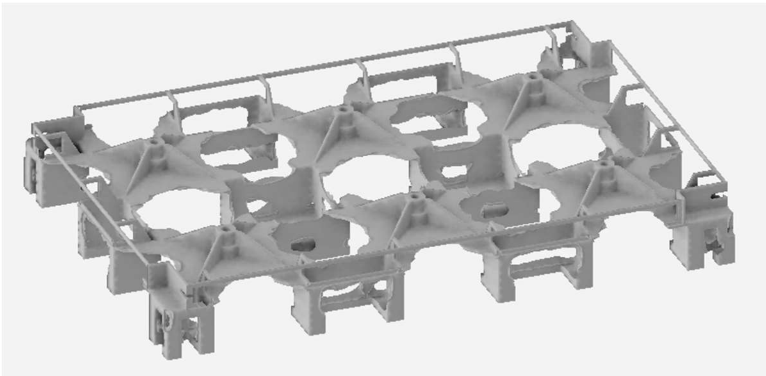


figure 77: optimized topology of the base part

5.2 Weaknesses

The weaknesses of this design address geometrical disadvantages of oversizing as well as the lack of material and manufacturing parameters of the final design.

Geometric Weaknesses
The dimensions of the PI Pallet must be listed as a weakness. Compared to current standard Pallet, the PI Pallet is 16% higher. The basis for this comparison is the height of a EURO Pallet [HK15, p135].
The design does also influence the width and length of the PI Pallet. Because of the mechanism of the inlay part, 12mm of space are required additionally on all sides. Because of the special telescoping mechanism within the PI Pallet Units, the additional space will not be multiplied by the number of used Single PI Pallets. This indicates an additional space required of 24mm for width as well as for length per PI Load Unit, regardless of the number of used Single Pallets. The outer dimensions, as well as this mentioned oversize, are shown exemplarily for a PI Pallet of the dimensions 1200 mm x 800mm in figure 78.

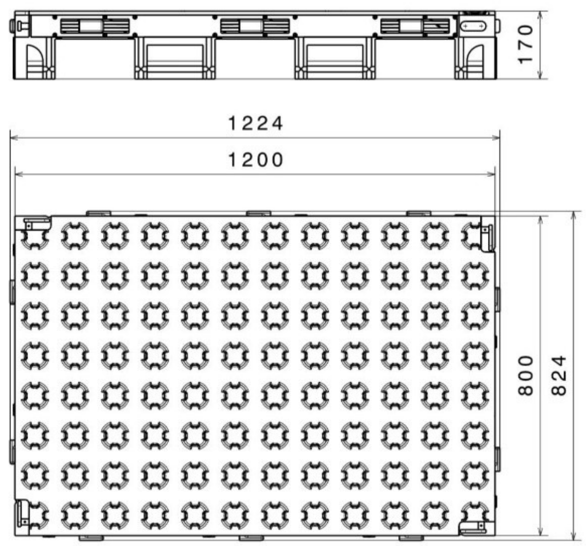


figure 78: oversize of a PI Pallet of dimension 1200mm x 800mm

Lack of Material and Manufacturing Parameters
The design process in this thesis does not specify any parameters concerning the material and manufacturing method. This assumption has been made to cover all potential design variants. This lack of material and manufacturing parameters does indicate that it is not possible to make precise statements about strength and weight in this thesis. All statements about strength and weight are based on assumptions.

5.3 Opportunities

The opportunities of the final design do address the features, concerning the interconnectivity between PI Pallets and PI Containers or PI compatible load carriers, as well as the capacity to handle the load with a forklift.

Operability of Forming PI Palletized Load Units
In order to address PI tasks, a PI Pallet Unit will be connected to one or more PI Containers. The mechanism included in the container will fulfil this connection. The PI Pallet is merely a passive part of this connection process, but it provides the basic geometry. The PI Pallet can be easily adapted to any PI Container connection technology by exchanging the top part. PI Containers can be easily and quickly connected to one or more PI Pallets by using the connection technology located on the PI Container. The disconnection process is as easy and fast as the connection process. Figure 79 shows a PI Palletized Load Unit formed of two PI Pallets of the dimension 1200mm x 400mm as well as two PI Containers of dimensions 600mm x 400mm x 400mm.

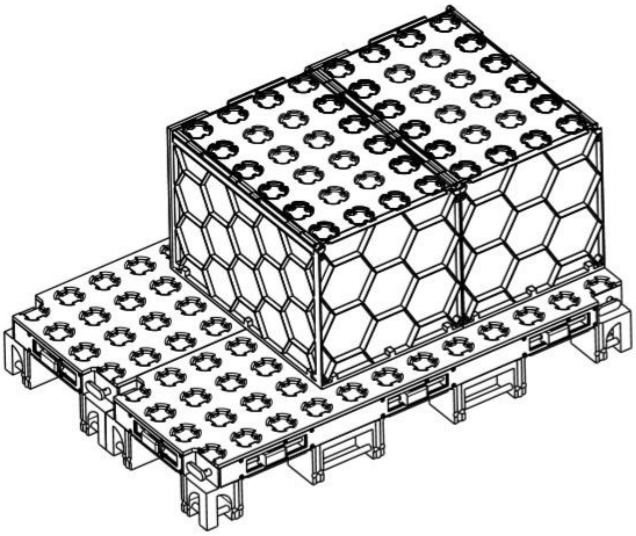


figure 79: PI Palletized Load Unit

Load

For a rough estimation of the strength of the connecting mechanism, the system was simulated by an FE software. The simulated process was the handling process of lifting a PI Palletized Load Unit consisting of two PI Pallets. Following assumptions were made in order to simplify the simulation process:

- The considered PI Palletized Load Unit consists of two PI Pallets of the dimensions 1200mm x 800mm, connected by their long side.
- As explained in chapter 4.1.2, the maximum load for handling processes was defined as 1500kg per pallet.
- The point of gravity was defined in the middle of each PI Pallet.
- The position of the forklift was assumed as shown in figure 80
- The elements which will be most stressed within this handling process are the hooks
- The hooks are made of a state-of-the-art stainless steel

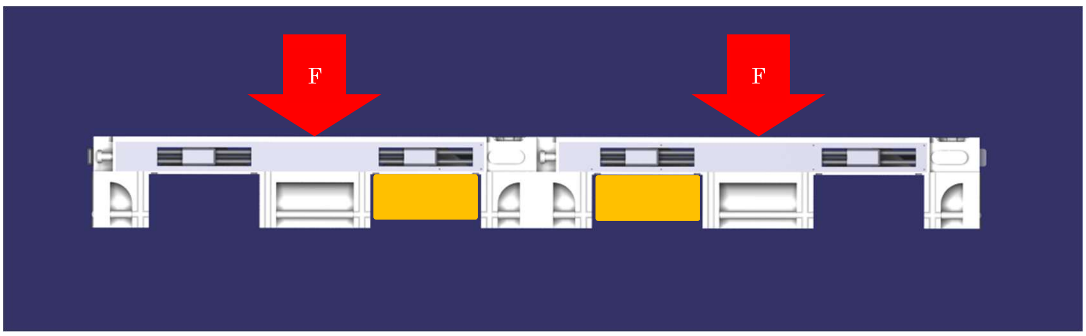


figure 80: load situation for simulation

According to the load situation shown in figure 80, the stress situation in the hook was simulated. Figure 81 displays just a rough estimation based on the assumptions listed before. This figure shows the magnitude (left) as well as the equivalent stress (right) within the part.

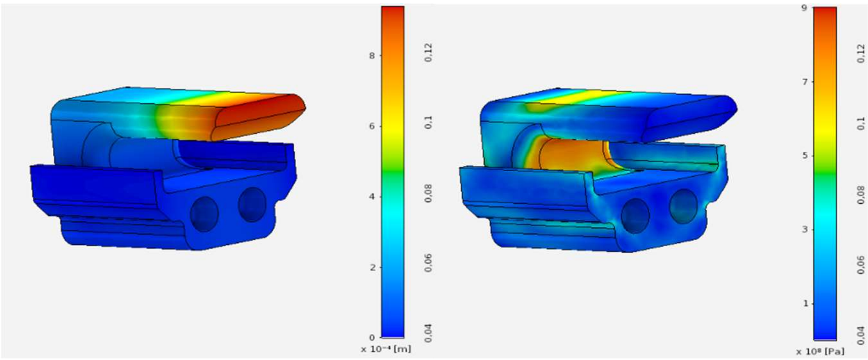


figure 81: outcome of the FE simulation of the hook

5.4 Threats

According to the methodical design of the Base part, different handling situations can lead to instability while lifting the PI Palletized Load Unit or Single PI Pallets with a forklift. In order to ensure security during operation, such situations, exemplarily shown in figure 82, must be prevented from happening by using additional safety appliances or forklifts with adjustable fork distance.

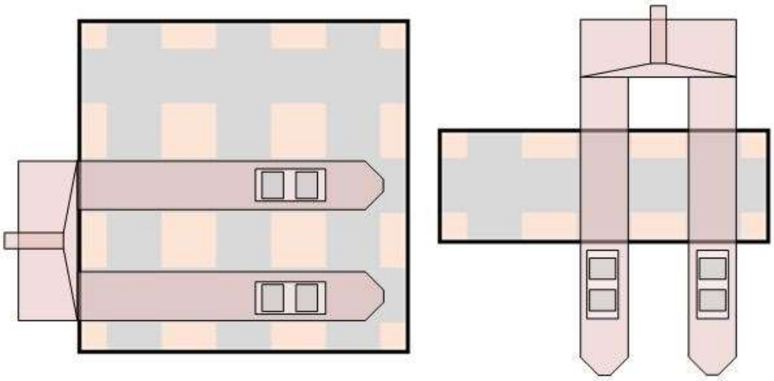


figure 82: potential handling instabilities

6 Outlook

This thesis outcome serves as the first step in the process of PI Pallet development and their implementation in the logistics and transportation branch. The design process in this thesis, outlines the general constraints and basic conditions as well as a rough design of a PI Pallet system. In order to reach the goal of implementing this tool in potential future PI scenarios, further developmental steps must be taken. This can be achieved by pursuing theses or projects. Possible contents of such theses or projects can be:

- Further material research and geometrical optimization
    a) Optimization of geometry and design as well as further precision of load situation, proof of strength and FE simulations.
    b) Material choosing process according to manufacturability and suitability to PI philosophy
- Development of additional features and add-on part
    a) Research about additional needs and wishes as well as development of additional features
    b) Methodical development of add on-parts suitable for PI Pallets (e.g. rolls, grids, etc.)
- Usability studies
    a) Field studies and readiness analysis of a PI Pallet concept for compatibility and usage in a future PI scenario
    b) Research about additional scenarios and further use cases of PI Pallets in the logistics and transport branch
    c) PI Pallet pooling systems and their economic impact as well as the readiness for PI
    d) Knowledge transfer from and to other fields of research

Parallel to that additional research and development processes, the virtual prototype, developed for this thesis can be turned into a physical prototype to use it for diverse testing and research about actual compatibility with PI elements in order to create more data for her developmental steps and to support further research processes.

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date: 14.09.19

7.2 List of Figures

7.3 List of Tables

7.4 List of Used Software

Visio 2016

creating of visualizations, figures and flowcharts

Catia V5R19

mechanical design of components, assemblesand technical drawings

ANSYSY Discovery Live 2019

simulation and visualization of mechanical behaviour of components