

Modular Boxes for the Physical Internet – technical aspects

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0. Abstract

One of the main key enabler for a successful realization of the Physical Internet scenario is the design of a modular box that fulfils all requirements of an interconnected logistic network. To address all these requirements a holistic approach including all needs of the shipping network is integrated in the methodical development process that leads to the modular box prototype.

This paper illustrates the engineering process starting the first approach to develop a modular and multifunctional load unit to make a Physical Internet scenario working. The process starts with the research for the optimum box sizes, the identification and further integration of the needs of a Fast Moving Customer Goods supply chain. This continues in virtual and practical proofs of concept including engineering aspects and prototypes as well as the shipping scenario within supply chain constraints.

1. Introduction

Megatrends like urbanisation and individualization force logistic distributors to make their business more and more efficient, with minimized logistic costs by facing an increasing volume of one-item-delivery. This is well known from the e-commerce business. The nearly same important logistic challenge lies within the area of fast moving consumer goods (FMCG).

FMCGs are pharmaceutical, consumer electronic, personal care, household care, branded and packaged food, spirits and tobacco. Although the range of products is various, most of them are consumed frequently, branded, packaged and sold at a low price, mostly in developed countries. The FMCG sector is engaged in production, distribution, marketing and general management of consumer packaged goods. It is alternatively referred to as CPG for Consumer packaged goods. Regularly these goods have a quick turnover and relatively low costs. Those products are normally consumed by the end-customer at a frequent interval. Generated profits are relatively small, hence the products are sold in large quantities. The accumulation of different companies is also represented in the diversity of the goods caused in the broad portfolio of fast moving consumer goods. The FMCG supply chain (SC) focuses on an institutional, stationary trade in universal and specialized retails stores with a trend towards eCommerce. Although the range of products is various, most of them share the same characteristics:

- Used directly by the end-consumer
- Non-durable
- Sold in packaged form
- Are branded
- At a low price
- With high volumes
- Used at least once a month (frequent purchase)

Fifty percent of the most successful FMCG-companies in regard to the Forbes list are rooted in North America and in Europe, respectively. Within the most potential players in the fields of manufacturing is Procter & Gamble (P&G) in the US and Nestle in Europe. The top retailer is Wal-Mart Stores in the US and Metro AG in Europe.

The handling of FMCG in dedicated supply networks takes place in central and regional warehouses. The five main process steps within a logistics centre are the goods receipt, storing, consignment, storing again, and goods issue [23]. Supported are the main tasks by transportation, handling, and packaging processes as well as administration processes [1]. Main challenges with logistics at all can now be identified as [4]:

- We are shipping air and packaging
- 25% of all miles are empty!
- 56.8% "full" trailers when not empty!
- 42.6% average utilization
- \$65.8 billion opportunity in the US alone!
- Congestion is high with \$1008/yr in wasted fuel and lost time!
- CO₂ emissions are growing 233.8 Tg CO₂ emissions opportunity!
- Truckers have become today's modern cowboys
- 100%+ turnover rate in the industry!
- Demonstrable negative health benefits!

Focussing those challenges the Physical Internet (PI) Initiative tries to address them as an open global logistics system founded on physical, digital and operational interconnectivity through encapsulation, interfaces and protocols. The aim of the PI is to enable an efficient and sustainable logistics web at the logistic hubs as well as at the end consumer, where current systems aren't efficient enough to address the outlined megatrends.

First steps in realizing the PI visions have been started in the project MODULUSHCA which is funded by the 7th Framework Programme of the European commission.

2. MODULUSHCA Vision and interconnection to physical internet (PI) [24]

MODULUSHCA (Modular logistics units in shared co-modal networks) tries to make major contributes by introducing the Physical-Internet (PI) to FMCG logistics. The main goal of MODULUSHCA is to provide solutions for better space usage and standardization as well as providing interchange scenarios and technology for shipping goods between continents. It is a three years research project with 15 partners from research, logistics and postal business and FMCG industry. Its objective is to achieve the first genuine contribution to the development of a much more efficient logistics, an interconnected logistics at the European level, in close coordination with North American partners and the international PI Initiative. The goal of the project is to enable operations with newly developed iso-modular logistics units of sizes adequate for real modal and co-modal flows of FMCGs, providing a basis for an interconnected logistics system seeking a significant two-digit improvement in operations' efficiency.

MODULUSHCA integrates five interrelated working fields [5]:

1. Developing a vision addressing the user needs for interconnected logistics in the FMCG domain;
2. Developing a set of exchangeable (ISO) modular logistics units providing building blocks for larger units
3. Establishing digital interconnectivity of the units;
4. Developing an interconnected logistics operations platform leading to a significant reduction in costs and CO₂ emissions;
5. Demonstrating the exploitation of the modular logistics units and of the interconnected platform in two implementation pilots for interconnected solutions.

The overall goals are [1]:

- To set the landscape by elaborating the PI enabled interconnected logistics vision and by developing and demonstrating core components of this vision.
- To achieve both a simulation-based and a field-based proof of concept by gradually implementing and testing key functions of interconnected logistics and involving key stakeholder groups through all development and implementation phases.

- To ensure a global synchronization with concurrent projects in the USA and Canada within the international PI initiative, and pave the way for a common and early market implementation at the intercontinental level.

The main benefits after the three year research period will be (started October 2012):

- Demonstrate the technical, digital and operational feasibility of seamless handling of cargo within SC operations across companies and transport modes.
- Recommending industry standards for iso-modular logistics units to be deployed along the entire SC of different branches for a European wide and global market introduction.
- Develop models to assess the SC benefits providing a methodology for cross process and cross company SC analysis for industry and policy makers.
- A clear information handling approach, including data consistency and transport monitoring along the journey as model contributing to extend and enhance standardization developments in eFreight and iCargo.
- Developing optimization algorithms for loading capacity optimization and scheduling transferring especially to SME user groups.
- Enhance the innovation process at the interface material and transport flow to stimulate a gradual market take up and implementation process.
- Stimulate the market uptake of new interconnected logistics systems and other innovations developed and tested within the project and thereby increasing the viability of the implementation.

One of the key components and enablers in this project are the modular logistic units. The team of Graz University of Technology is responsible for this research and the development process consisting of: defining the modularity, the sizes, collecting requirements, deriving functions, finding solution principles, develop functional features, designing the modular units and producing prototypes. The next chapters will deal with this work and will reveal the first physical object of the PI: The M-box.

3. The M-box – a key enabler

One enabling component of an interconnected logistics system is the modular logistics container to be designed and developed within MODULUSHCA. The innovative M-box development aims at a modular set of load units forming a building block of smaller units that can be combined manifold while respecting actual sizing requirements for efficient handling and space usage. Since the range of modular logistics containers will reach in the future from small sizes, over pallet sizes up to swap body or iso-container sizes, this first task aims to determine an initial set of units focusing on non-perishables FMCG. In addition, this project will focus on smaller sizes to be grouped together to standard pallet sizes. [2]

Today one has to distinguish between two categories of containers: The first category refers to as “handling containers”. Examples of handling containers today are cartons, cases, boxes and pallets used to cover product or provide a means to handle products together as a unit load. (Note that for most products today, the product itself provides the structural integrity of the handling containers; as opposed to the handling containers) The second category refers to as “transportation containers”. Examples of transportation containers today are the international shipping container, train wagons, and truck trailers, used to transport handling containers. Unlike with handling containers, transportation containers must provide the structural integrity of the load and must be able to resist the elements. [2]

With the advent of the PI, its inventors assume that transportation containers will remain relatively unchanged. Perhaps, over time, their dimensions will be modified so as to synchronize them over a variety of modes (e.g., ship, rail, truck). However, it is an assumption that in a future vision with the PI, handling containers will be reduced to modular containers and unit loads that are built out of multiple modular containers. That is, the need for a pallet will be removed and modular containers will replace the cartons, cases and boxes used today. Going forward, in this section will refer to modular containers simply as M-boxes to make clear that M-boxes represent thoughts on the characteristics of modular containers used in the PI. [2]

To get aware of the relevant steps in the engineering design process of the M-box, which provides also the structure of this article, it is necessary to introduce the methodology already at this position. For the M-box development and design process the systematic approach of VDI 2221 [13] and VDI 2222 [14] (see Figure 1) is followed which is divided in 4 different phases. The following subchapters will now deal with the most important parts of these different phases and describe the work done to develop the M-box (see Figure 2).

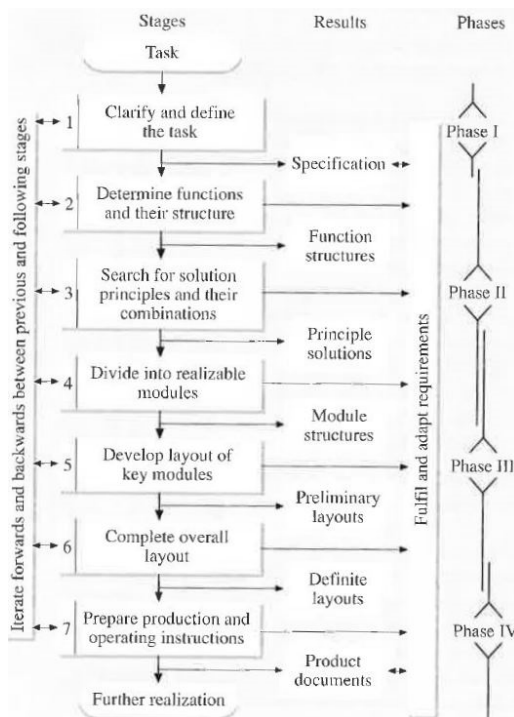


Figure 1: design process of VDI 2221 applied at the different phases of VDI 2222 [22]

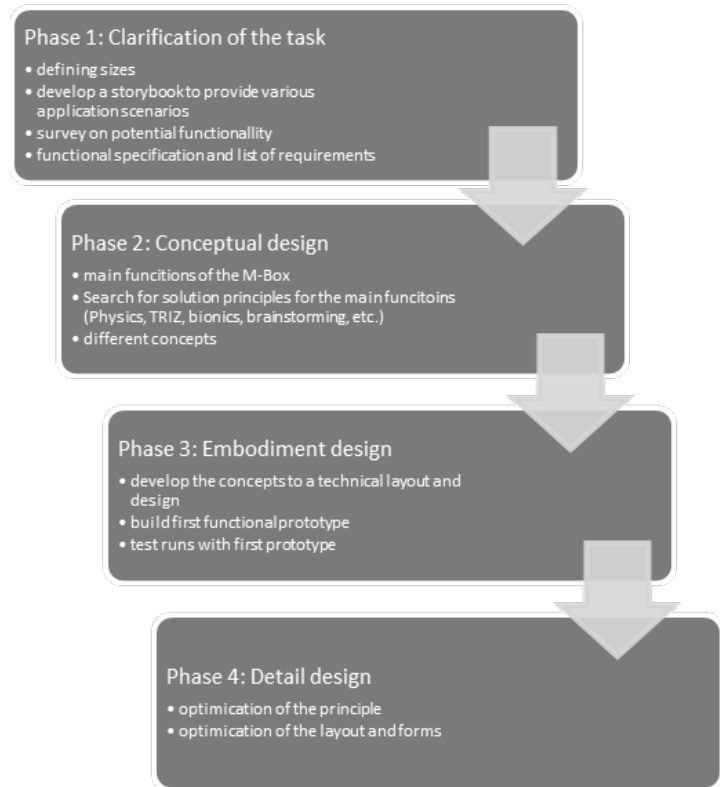


Figure 2: different phases of the VDI 2222 applied on the development process for MODULUSHCA, oriented on [14]

3.1. Defining sizes for M-boxes

Container loading problems (CLP) are well treated in (engineering) science. The CLP is usually defined as arranging rectangular items in cartons with the objective to minimize the total wasted space of the cartons, subject to loading constraints [12]. As surveyed by [17], the CLP is classified as the three-dimensional (3D) rectangular packing problem in the general cutting and packing problem literature. Some studies focus on applying two-dimensional (2D) pallet packing heuristics to a general 3D-CLP [18], whereas others focus on the practical aspects of loading a carton and develop solution approaches according to the concept of organizing loaded items. Because the CLP is an NP-hard problem [25], heuristic-based approaches become a necessary avenue of investigation if solving large instances of the 3D-CLP. Although these formulations provide valuable insight on the CLP, they assume that a set of cartons with known dimensions is given. The models then select a number of cartons to pack a given set of products. However, within the MODULUSHCA work a model that can be used to assign a set of standard modular containers to a variety of products is proposed [6], [7] (see those references also for details of the algorithm).

In today's SC for FMCGs the diversity of brands and types of products with various sizes and weights leads to a nearly infinite range of different sizes of carton boxes. Building unit loads with such a high variance of cases is rather complicated and leads to inefficient space utilization at the pallet level and as a consequence also on a truck level. Therefore the first problem to solve can be stated accordingly: For the FMCG market, determine the set of modular container dimensions that would balance the desire to decrease the number of options while at the same time not overly restrict options, because to do so will result in handling containers that are less full than today. In doing so, one has to consider that FMCG products that are shipped today have specific item dimensions and are shipped in specific quantities of items per handling container [8].

One of the first decisions to be made in specifying a set of modular containers is the "platform" for the set. That is, if one defines the platform's width, W , depth, D , and height, H , then the possible dimensions of containers that are modular to the platform can be chosen. At the outset one considers the European trailer dimensions and the current Euro pallet dimension. As the dimensions of the Euro pallet are 0.8m by 1.2m and the inside dimensions of the Euro trailer are 2.44m wide by 13.40m deep by 2.5m tall, the modular M-box platform can be

0.8m (W) by 1.2m (D) by 2.4m (H). Note that it is also considered a platform of 1.2m x 1.2m x 2.4m and other platforms based on the international shipping container. However, such a footprint would not utilize the current European trailer as well as the rectangular 0.8m x 1.2m footprint. To further refine this all three dimensions (0.8m, 1.2m, and 2.4m) are divided by 1, 2, 3, ..., as long as the result was greater than or equal to 0.1m. These dimensions would be considered exterior dimension standards. Then, based on many discussions, all combinations of x, y, z that were not integer at the mm level (that is, eliminating an x-value of 266.7mm formed by dividing W by 3 because 266.7 is not an integer) were eliminated; including a few other values (e.g., y = 150mm, and z = 160mm, 150mm). The reduced set of modular container dimensions is presented in Figure 3.

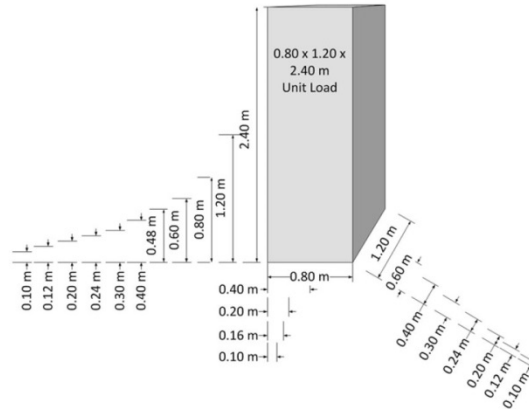
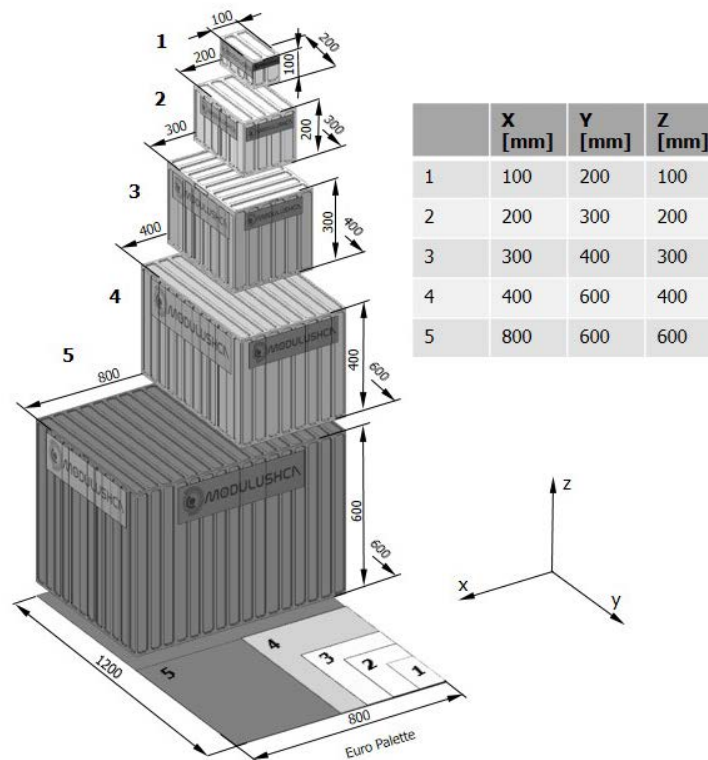


Figure 3: Modular Platform with 440 different M-box dimensions [9]

With this platform presented in Figure 3 the total possible number of M-boxes would be 440. These 440 different sizes of boxes can be considered to be a platform for further development and as a starting point for the recommended set of pooled containers. They are recommended by the MODULUSHCA consortium to maintain container fullness as much as possible and to improve overall utilization at the unit-load level. However, decisions around final platform selection will be iterative, subject to cost, industry and retailer support and also subject to the future development of the products in the FMCG Industry. Moreover, in addition to the benefits of a modular platform, there are benefits that can result if a small number of dimension combinations are in use in an asset pooling arrangement.

To show where this development can lead, a scenario where a data set of 1186 different products, all currently shipped by the consortium member P&G, is used to calculate the optimum set of M-boxes for this particular data set. This diverse and representative portfolio is used to drive the optimization and efficient trailer loading when considering mixed unit loads (see chapter 4.2). In order to develop an affordable and effective solution for MODULUSHCA that can be implemented in the market place and adequately leverage the benefits of pooling, five (5) different sizes of the M-box are presented in Table 1 (shown as outer M-box dimensions). These 5 different sizes can be considered as a first recommendation for a future build, still keeping in mind that engineering issues that will have an impact on the sizes and shape of the M-box will be addressed and resolved in the design stage. Furthermore, the test runs with the prototypes (see chapter 5) and the lessons learned from it will also have influence on the final set of M-boxes.

Table 1: proposed outer dimensions for the M-box



Whilst this selection is not directly modular with each other, they are with the modular “platform” (1.2m x 0.8m x 2.4m). Moreover, it is still possible to build loads as long as they are modular to the unit load level and additionally, it is possible to build unit loads on a different unit load platform. The 5 sizes chosen are still compatible to the needs of a modern pooling business model. A future option is to build the boxes not as a rigid box but out of panels. This means that a panel can be used as a side-, bottom- or top panel and allows building many different box sizes out of less different panels. For the MODULUSHCA project the consortium decided to put the focus on rigid boxes which are compatible with today’s SC systems. In order to show how a future scenario can look like the innovative idea of panels will be further developed virtually (see chapter 5).

3.2. Defining functions and specifications for M-boxes and unit loads [2]

After defining the sizes for the M-box units the next step is to develop a clear functional specification of logistic containers in FMCG. The functions and specifications are analysed using two different approaches: The Box and unit load functions from technical restrictions and box functions from logistics SC demands.

3.2.1. Box functions from logistics SC demands

A key enabler of this work is to develop a functional specification for the modular units. To do this requires a better understanding of cross industry and sector views, of the type of functionality that is desirable. Insight into what traits are considered most important via appropriate stakeholder input, enables identification and prioritization of potential design features. In order to capture as full an array of stakeholder views as possible from which to define the suite of functionality requirements, an e-survey is used to solicit input. The survey is based on a map of “typical” SC interactions between manufacturing sites, Distribution Centers, Co-packing sites and Retail outlets. These SC interactions are based on scenarios provided by a storybook approach (a particular example is outlined in Figure 4) focusing on particular aspects of the SC and on five focus areas:

- Reuse
- Repair
- Recycle
- Reach (also beyond EU)
- Ergonomics

The aim of this is to raise key questions around what the M-boxes should look like, how they may work and better understand how people should interact with them. The focus here is important. It is to understand or define functional need and not to attempt to identify solutions at this stage of the project. That will be addressed within chapter 3.3.

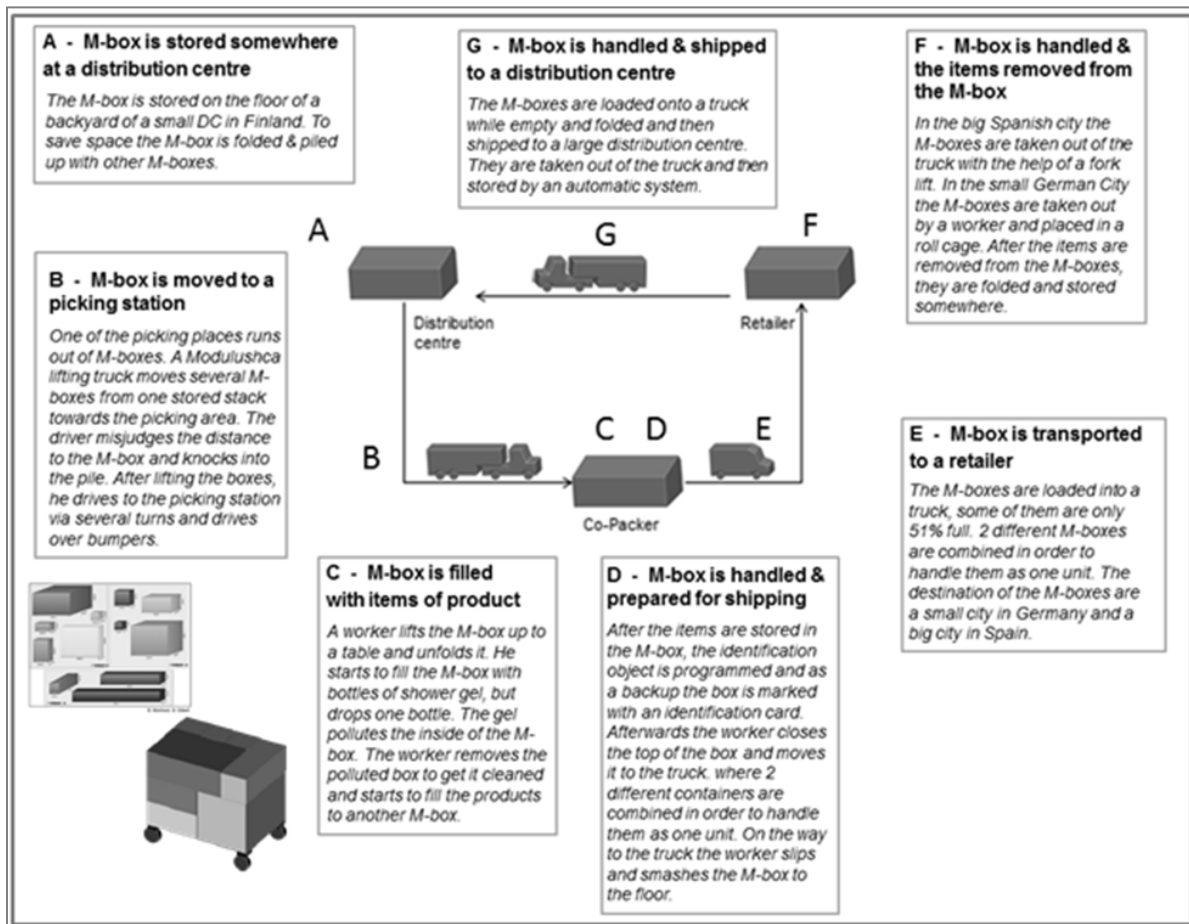


Figure 4: Storybook to sketch SC interactions for the survey

The result of the survey is to define “must have”-, “nice to have”- and “not required” functionality characteristic. The must have characteristics (outline in Table 7 at the appendix) are then used to derive the main functions of the M-box and also requirements for the design. These functions for the M-box used in the PI-Vision of 2030 are clustered to main functions and are listed below in Figure 5.

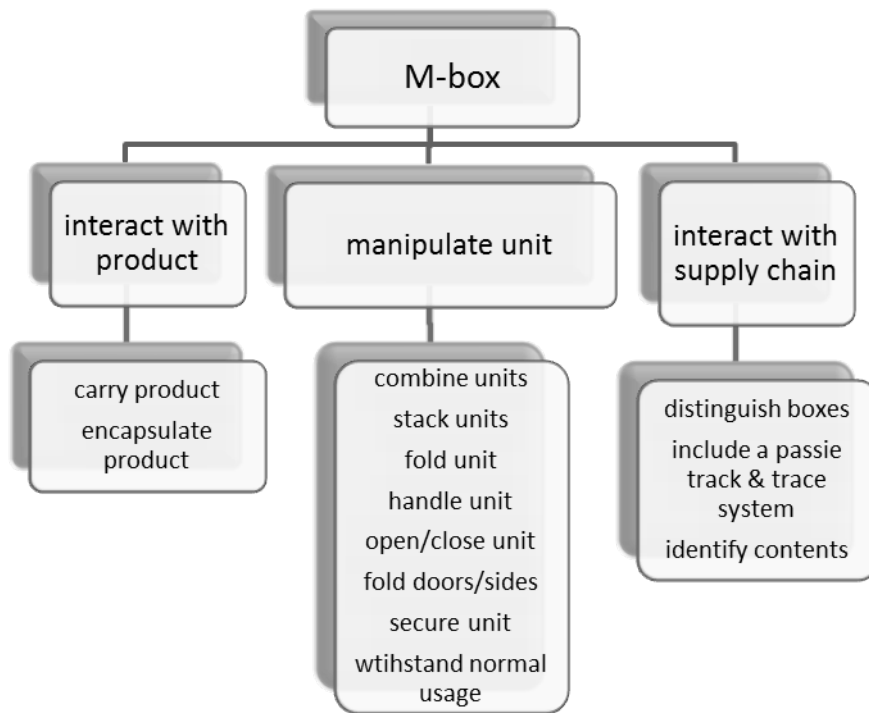


Figure 5: key functions the M-box

3.2.2. Box and unit load functions from technical restrictions

The development of a feasible PI-scenario requires that technical restrictions have to be identified and implemented in the engineering process right from the beginning. These technical restrictions which determine essential functions of the M-boxes and unit loads are specified by restrictions of law and guidelines as well as requirements resulting from the packing, shipping and loading processes [10]. To fulfil all these restrictions the whole process from packing the goods in the box, building unit loads and interlocking the boxes as well as the truck specifications have to be taken into account. The derived functions of the M-box and unit loads are categorized in two areas depending on their origin:

- restrictions from law and guidelines, which can vary from country to country
- requirements from the logistic processes as packing, loading and shipping

The technical restrictions determine mainly the maximum load an M-box has to withstand and the stability of the interconnected unit load. The stability of a unit load is according to BGR23 of 2006 [20] defined as the ratio between the moment of tilting which is generated by an applied force and the moment of stability as illustrated in Figure 7. This functions are the following:

- The M-box is built to load a maximum density of 500kg/m³ [2]. According to BGR23 of 2006 [20] the box has to withstand double the load resulting from the load in the box as well as the load of the boxes which are packed above in the packing pattern.
- In the PI-scenario special unit load stackers manipulate the unit loads which are built out of interlocked M-boxes. In this first development approach unit loads have to be carried on Euro-Pallettes. This may lead to weight limitations.

This leads to the fact, that the net weight of the smallest (empty) M-box in Table 1 has to be lighter than 0,37 kg, the biggest lighter than 106 kg.

Functions that are mainly influenced by the logistic processes (packing, loading and shipping) are identified by MODULUSHCA scenario simulations [19]. Therefore two relevant “logistic processes” are identified which are important for the box functionality and mainly influenced by technical restriction:

- 1) Building unit loads out of M-boxes
- 2) Allocation of the unit loads on the trailer

A limiting constraint for this first realization is that each unit load is built out of M-boxes of the same size that are filled with the same product. This leads to the fact that for each type of M-box the packing pattern for the unit load is previously fixed. So it is necessary to control if the unit load fulfils all restrictions of law and if it fulfils all technical specifications to be shipped. To identify technical restrictions from the complete shipping

process several algorithms that simulate a shipping scenario are developed. Figure 6 shows the analysis process combined with the developed tools, objectives and input data.

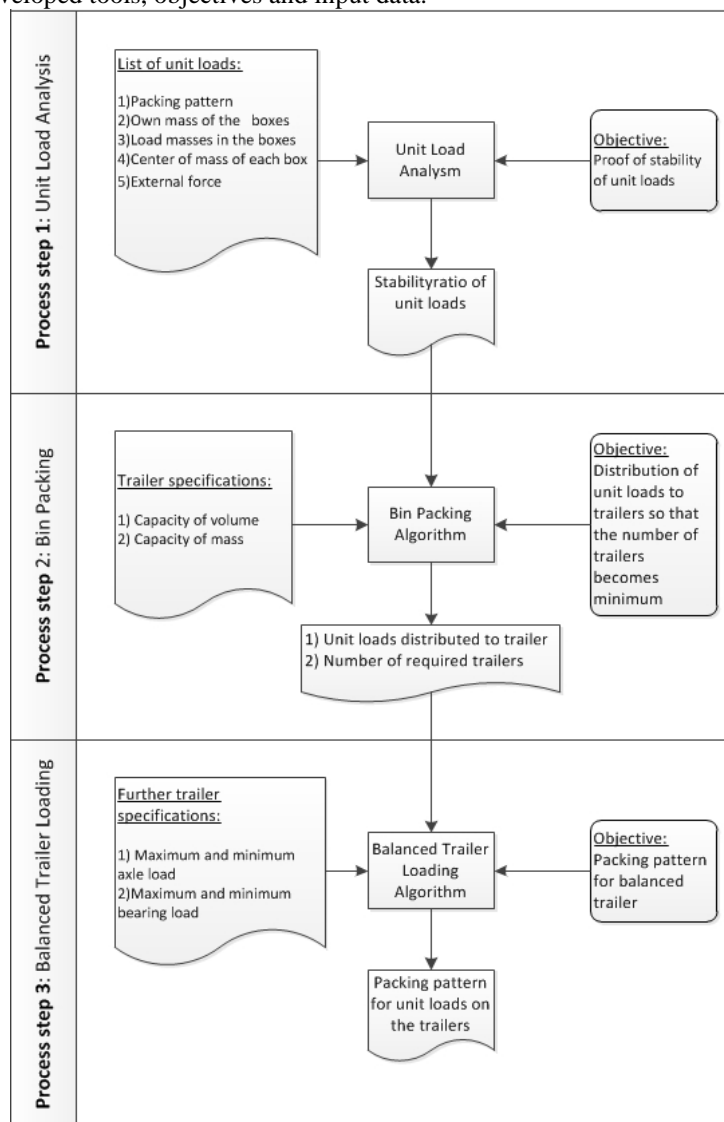


Figure 6: Process of packing, loading and shipping analysis [10]

One of the major points for the unit load analysis (process step 1 in Figure 6) is the stability of the unit load which is important for the M-box design. Therefore, the packing pattern of the unit load is analysed by taking into account the position of each M-box in the unit load, net weight of the boxes, payload in the boxes, centre of mass of each box and maybe an applied external forces. The result of this calculation is a ratio S , which is built by the moment of stability divided by the tilting moment (see Figure 7). Due to the fact that all M-boxes are interlocked the unit load can be seen as one unit and the calculation guideline from BGR23 of 2006 [20] can be adapted to the equation described in Figure 7. Additional loads from transportation dynamics, as outlined in [15], are not subject of this considerations.

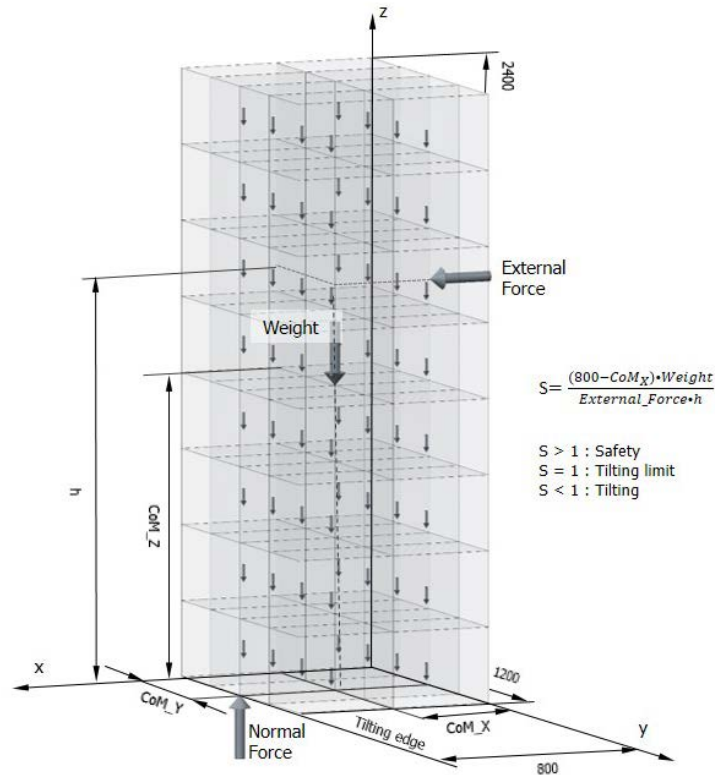


Figure 7: Forces on unit load and stability

To ship the unit loads they have to be positioned on trailers. Based on the facts that the number of possibilities to position the n unit loads increases with $n!$ and the problem is NP-complete [11] the second logistic process “Allocation of the unit loads on the trailer” was split up in two sub-processes (process step 2 and 3 in Figure 6). The first sub-process distributes the unit loads to trailers so that the number of trailers becomes a minimum. In literature also known as “Bin Packing”. The second sub-process places the unit loads on the trailer on their precise position in a way that the maximum and minimum axle load and bearing load of the trailer are fulfilled. This algorithm is further called “Balanced Trailer Load”-Algorithm.

Bin Packing Algorithm

As outlined in chapter 3.1 multiple container loading algorithms are well documented in literature. For several reasons (i.e. not addressing lower bound) these heuristics don't fit the M-box bin packing problem. Exact algorithms (i.e. exact branch and bound algorithm in [11]), to solve this packing problem, would need too much calculation time for the big number of unit loads ($> 16,000$ for PI scenarios) to distribute. Commercially available products like [26] don't allow detailed analysis of the used algorithm and therefore can't be assessed. The algorithms introduced earlier in this work use heuristics or semi heuristics approaches. Bin packing, means assigning a given number of defined items to load units by minimizing the number of these units, is a combinatorial problem.

The main objective of M-box bin packing is to distribute a given amount of unit loads of the same size but different weight to trailers of the same type so that the number of trailers becomes a minimum. All the trailers have the same capacity of weight (24,000kg) and volume (33 unit loads) so a trailer can be full in two ways: packed with 33 unit loads or weighing 24,000kg. The basic assumption of the developed algorithm is that the optimum number of used trailers can be reached if the trailers are charged to both capacities. So the objective of the algorithms distribution process is to assign as many unit loads on each trailer so that packed weight becomes exactly the determined weight. The mathematical formulation of this process is very similar to the “Bounded Change-Making-Problem” with the difference that here as many as possible unit loads get packed. A few solution approaches are documented in literature [11] which are mainly based on exact, heuristic or semi heuristic algorithms. Limiting boundaries for the different approaches are outlined above (due to the large number of unit loads). Therefore a semi-heuristic algorithm based on the rolling horizon approach is developed. Additional boundaries are that each unit load has the same footprint but differs in weight and all unit loads have the same shipping destination; this addresses the main requirements of PI ideas. Figure 8 depicts the developed “Bin Packing” algorithm and its variables, which are explained in detail below.

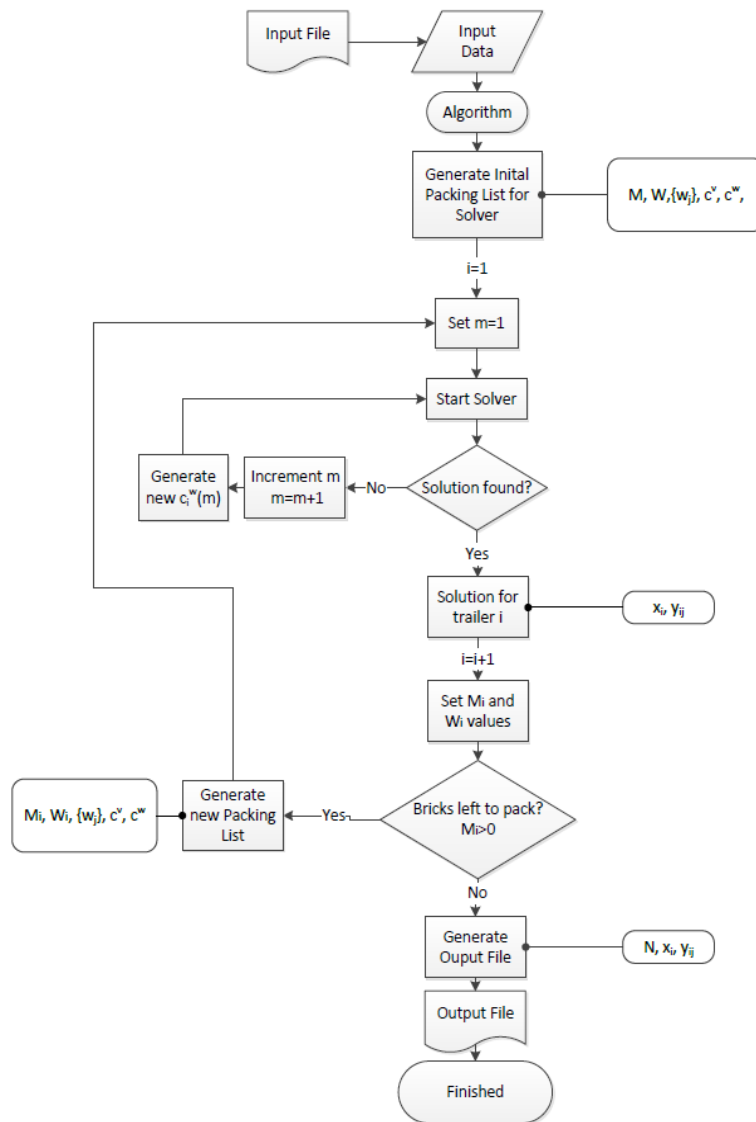


Figure 8: Flow Chart "Bin Packing" Algorithm

Notation

i = index for trailers

j = index for ULs

m = index for solver runs while packing trailer i

y_{ij} = decision variable for UL j assigned to trailer i

x_i = decision variable for trailer i

M = total number of ULs

M_i = number of ULs for packing trailer i

W = total weight of ULs

W_i = total weight of ULs for packing trailer i

N = number of required trailers

w_j = weight of unit load j

c_i^v = capacity of volume of trailer i

c_i^w = capacity of weight of trailer i

$c_i^{w(m)}$ = modified capacity of volume of trailer i and solver run m

Assuming that all packed trailer have the same capacity of weight and volume leads to $c_i^v = c^v$ and $c_i^w = c^w$ for $\forall i$.

Sets:

The sets define the number of unit loads $j \in L$ where $|L| = M$, the number of trailers $i \in T$ where $\sum_{i=1}^M x_i = N$ and the number of solver runs while packing trailer i with $m \in \mathbb{N}^+$

Limits:

The number of unit loads that are available for the first trailer to pack is the total number of unit loads $M_1 \equiv M$ and lowers with each packed trailer (Equation 1).

$$M_i = M_{i-1} - \sum_{j=1}^M y_{ij} \quad \forall i > 1 \quad \text{Equation 1}$$

The total weight of all unpacked unit loads for the first trailer is $W_1 \equiv W$ and lowers with each packed trailer (Equation 2).

$$W_i = W_{i-1} - \sum_{j=1}^M y_{ij} * w_j \quad \forall i > 1 \quad \text{Equation 2}$$

For the first solver run $m=1$ on trailer i the modified capacity of weight is $c_i^w(1) \equiv c^w$ for $\forall i$. For each further solver run the modified capacity of weight lowers about ten (Equation 3).

$$c_i^w(m) = c_i^w(m-1) - 10 \quad \forall i; \forall m > 1 \quad \text{Equation 3}$$

$$x_i, y_{ij} \in \{0,1\} \quad \forall i; \forall i, j \quad \text{Equation 4}$$

Decision Variables:

The algorithm determines which unit loads to pack on each trailer.

$$y_{ij} = 0 \text{ or } 1 \quad i, j = 1, \dots, M > 1 \quad y_{ij} = \begin{cases} 1 & \text{if UL } j \text{ is placed on trailer } i \\ 0 & \text{otherwise} \end{cases} \quad \text{Equation 5}$$

$$x_i = 0 \text{ or } 1 \quad i = 1, \dots, M \quad x_i = \begin{cases} 1 & \text{if trailer } i \text{ is used} \\ 0 & \text{otherwise} \end{cases} \quad \text{Equation 6}$$

Objective:

The solver objective is to maximize the number of unit loads on each trailer.

$$\text{maximize } \sum_{j=1}^M y_{ij} \quad \forall i \quad \text{Equation 7}$$

Constraints:

There cannot be more unit loads packed on the trailers than the total number of available unit loads: $N = \sum_{i=1}^M x_i$.

The solver can pack one trailer i at once and “opens” the next trailer $i+1$ after trailer i has finished: $\sum_{i=1}^M y_{ij} = 1$ for $\forall j$

Volume-constraint: The maximum number of unit loads on the trailer is the capacity of volume c_i^v of trailer i $\sum_{j=1}^M y_{ij} \leq c_i^v$ for $\forall i$.

Weight-constraint: The loaded weight of the unit load on trailer has to be equal the trailer’s capacity of weight c_i^w (Equation 8). If the solver cannot find a solution, the capacity of weight c_i^w becomes the modified capacity of weight $c_i^w(m)$, lowers about ten, the number of solver runs m rises about one and the calculation process starts again (Equation 9). This procedure runs until a solution is found or the modified capacity of weight $c_i^w(m)$ becomes zero.

$$\sum_{j=1}^M y_{ij} * w_j \equiv c_i^w(1) \equiv c^w \quad \forall i, m = 1 \quad \text{Equation 8}$$

$$\sum_{j=1}^M y_{ij} * w_j \equiv c_i^w (m - 1) - 10 \quad \forall i, \forall m > 1 \quad \text{Equation 9}$$

$$x_i, y_{ij} \in \{0,1\} \quad \forall j; \forall i, j \quad \text{Equation 10}$$

Parameters:

Each particular problem that has to be solved has the following parameters that differ. $L(M, W, \{w_j\})$ & $T(c^v, c^w)$

Lower Bound:

The Lower Bound (LB) is the theoretical minimum number of trailers that can be reached to ship the given amount of unit loads. The Lower Bound is determined by the trailer's capacity of weight and volume and the amount, size and weight of the unit loads. Two sorts of Lower Bound can be differed:

Lower Bound of weight (Equation 11)

Lower Bound of volume (Equation 12)

The lower bound, which is bigger, is the minimum number of trailers that can be achieved by the packing process (Equation 13)

$$\text{Lower Bound of weight} \quad LB^w = \left\lceil \frac{W}{c^w} \right\rceil \quad \text{Equation 11}$$

$$\text{Lower Bound of volume} \quad LB^v = \left\lceil \frac{M}{c^v} \right\rceil \quad \text{Equation 12}$$

$$\text{True Lower Bound} \quad LB = \max \{LB^w, LB^v\} \quad \text{Equation 13}$$

Example (Table 2):

5 ULs with 900 kg/UL

20 ULs with 800 kg/UL

27 ULs with 500 kg/UL

19 ULs with 300 kg/UL shall be packed on trailers.

M= 71

W = 39,700 kg

$w_j \in \{900,800,500,300\}$

$c^v = 33$ ULs/trailer

$c^w = 24,000$ kg/trailer

LB= 3

Table 2 lists the results of the example data. It shows that the Lower Bound is reached and that each trailer carries the maximum load combined with the maximum reachable number of unit loads (UL). The algorithm is implemented in Microsoft EXCEL 2013® "non-linear" solver application as seen on Figure 8 and tested with the shipping data of a representative distribution centre. In all cases tested, the heuristic produces solutions that are either optimal or within one trailer of a lower bound.

Table 2: Results of the "Bin Packing" algorithm (example)

Trailer No.	Total number of UL []	Total weight [kg]	Number of UL []	UL weight [kg/UL]
1	33	24,000	1	300
			8	500
			19	800
			5	900
2	33	14,200	13	300
			19	500
			1	800
3	5	1,500	5	300

Balanced Trailer Load Algorithm

The "Balanced Trailer Load" algorithm is an evolutionary algorithm. The aim of this algorithm is to allocate the unit loads on each single trailer on their specific position. The algorithm "packs" one trailer with the input data generated by the "Bin Packing" algorithm.

As an example a typical german trailer is used. The restriction of law by the road traffic act in Germany and technical restrictions define the boundaries. Figure 9 shows a significant result of the algorithm and depicts the boundaries, centre of mass, axel- and bearing load.

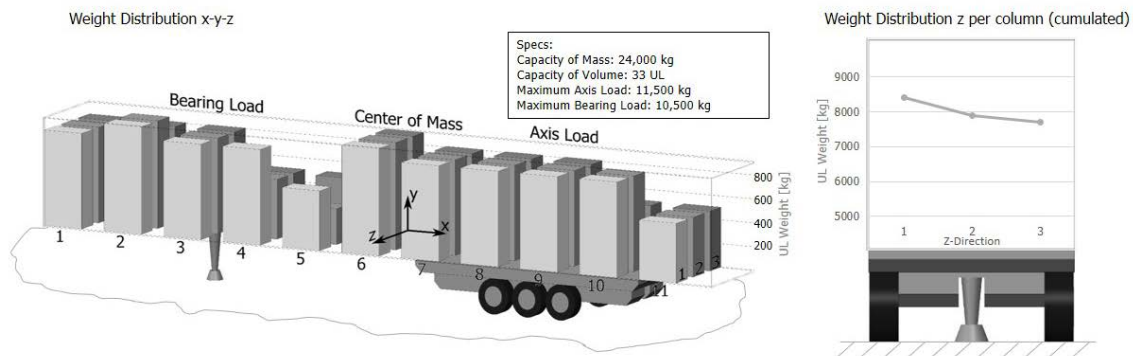


Figure 9: Balanced Trailer Loading

3.3. Designing the M-box

To design the M-box one major point is still not considered: How to proof the future MODULUSHCA concept in today's SC. Along with the virtual proof (VP) of concept by simulation, the MODULUSHCA concept will also be tested in various practical proofs (PP) as test runs including a real prototype (see chapter 4 and 5). In those test runs various developments will be practically demonstrated in different demonstration environments. To use the prototype of the M-box effectively at the demonstrations and to achieve test results which are highly objective and represent a broad range of different SC scenarios the consortium decided to split up the proof of concept into three different parts (see Figure 10):

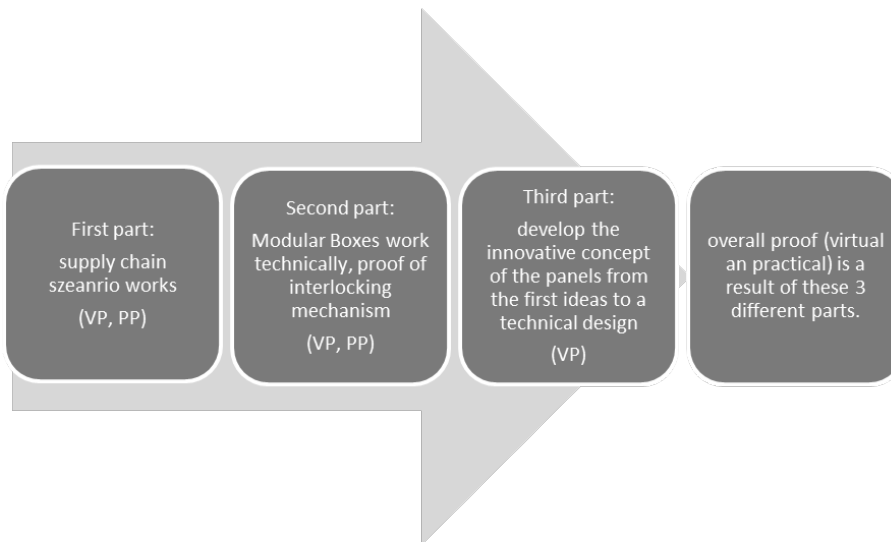


Figure 10: steps to prove the MODULUSHCA concept [3]

Part:

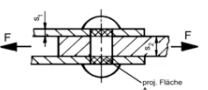




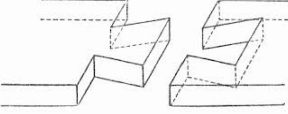
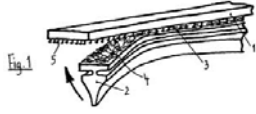
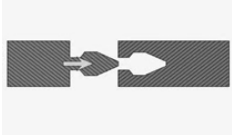
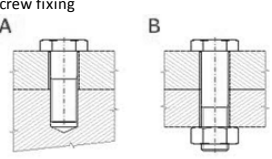

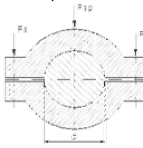
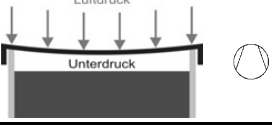
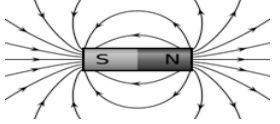
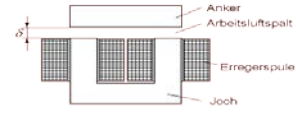
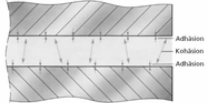

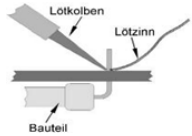
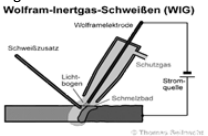
- 1) SC scenario works:
To prove the assumptions made in the simulation of the SC scenario (see chapter 4.2) standard boxes will be bought which meet a lot of the functions and requirements of the M-box. These boxes can be low cost and will be used in one part of the practical test runs.
- 2) Modular Boxes work technically with the new innovative function of interconnecting:
A conclusion of a policy and market analysis is that there are already a lot different transport boxes on the market meeting most of the essential requirements [3]. They are modular, foldable, stackable, etc. but none of them has an interlocking system meeting the demands of the PI-Vision. This is why the main focus in the design process is on the innovative interlocking mechanism.
For this proof the prototypes are built iteratively to investigate and test the interlocking mechanism. The design will therefore not meet all the requirements and functions outlined in the functional specification (see chapter 3.4). The design will mainly focus on the interlocking mechanism and can't be seen as the final design for the M-box of 2030.
- 3) Further develop the innovative concept of the panels from first ideas to a technical design:
As outlined in chapter 6 building M-boxes out of panels will need a change in today's SC and how transport units are used in interconnected logistics.
This research and development process will take the first ideas of how to realize M-boxes out of panels and will evolve the concept to a technical design. It will give solutions of how to overcome the technical obstacles and problems of such a development.

The consortium strongly believes that proofing those three different parts will prove the overall concept of MODULUSHCA. It will mean a huge step into the direction of an interconnected logistics and takes the PI to a new level.

3.3.1. Designing the interlocking mechanism

Following the different phases of the VDI 2222 [14] (as described in Figure 2) the next step is to find solution principles for the function "combine units". For this, different physical effects are investigated in respect to the functions to find possible solutions (see Table 3).

Table 3: selection of solution principles to combine the units

manipulate units subfunction: combine units			
possible solution solution principle based on a physical effect.			
1. mechanically tight fit (contact pressure) using loose parts	1.1 rivets 	1.2 male/female forms 	1.3 splints 
	1.4 bolts 	1.5 tenterhook 	
2. mechanically tight fit (contact pressure) without using loose parts	2.1 male/female forms 	2.2 hook and loop fastener 	
	2.3 spring lock 		
3. mechanically force fit (friction)	3.1 screw fixing 	3.2 connection with chocks 	3.3 clamped connection 
	4.1 Vacuum by pump Luftdruck Unterdruck 		
5. magnetically magnetic field	5.1 permanent magnet 	5.2 electromagnet 	
	6.1 sticking 	6.2 SMA (Shape-memory alloy) 	
7. thermally melting	7.1 brazing 	7.2 welding Wolfram-Inertgas-Schweißen (WIG) 	

To further assess the different principles and to focus the further developing work on the most promising solution they are evaluated following the methodology of Pahl/Beitz [16] by different criteria:

- Compliance with the overall task
- Fulfills demand of the specification
- Realisable in principles
- Within permissible costs
- Incorporates direct safety measures
- Preferred by designer's company

In the next steps developing tools like the TRIZ method and brainstorming in a larger team helped to find more detailed solutions to realize the function “combine units”. For the innovative interlocking mechanism a male/female system situated on top and at the bottom of each box is chosen, due to comprehensive and broad assessment results.

3.4. Design-drafts for the Box-prototypes

After several iterations in the design process (see also [3]) the drafts are evolved to the design of the first prototype (see Figure 11).



Figure 11: First M-box prototype design

Table 4: KPI's of the first M-box prototype

KPI - M-box (actual prototype design)	
Outer dimensions [in mm]	300x400x300
Inner dimensions [in mm]	270x360x275
Volume usage	74.25%
Weight	6.7kg

Using 3D printing technologies like stereolithography and laser sintering the first prototype (see Figure 12) is produced as a starting point for functional tests and design evolution. With a total weight of 6.7kg and a volume usage of 74.25% (see Table 4) the M-box is heavier than similar transport boxes (~2.5 to 3.5 kg) and has an average volume utilisation (compared to 70% to 80% of similar transport boxes). As stated in chapter 3.3 the focus of the first prototype is on how to combine the units with the interlocking mechanism. Therefore it does not fulfil all the functions and requirements (see Table 5), is not a lightweight design (due to 3D-printing and cost limitations) and still leaves the opportunity to improve the volume usage up to 85%.

As already stated before, the innovative interlocking mechanism is realized with a male/female system situated on top and at the bottom of each box. To build a unit load the different M-boxes have to be positioned on top of each other in a criss-cross packing pattern. Using a handle which is positioned at the top of the M-box to activate or deactivate the interlocking mechanism is a matter of safety. If one M-box is positioned on top of another the mechanism can't be deactivated by accident and is self-secured.

Table 5: List of realized functions

x... not demanded, ☑... fulfilled



Figure 12: First physical Prototype

M-Box functions	fulfilled now	fulfilled at 2 nd gener.
fold unit	x	x
encapsulate product	☑	☑
carry product	☑	☑
Fold doors/sides	x	x
combine units	☑	☑
stack units	☑	☑
Distinguish boxes	x	☑
Open/close box	☑	☑
include a passive track & trace system	x	x
Identify contents	x	☑
Handle units	x	☑
withstand normal usage	☑	☑
Secure box	x	☑

The next step in the design process is to improve the design according to functional test results. The main goal is to reduce the weight and to increase the volume usage up to 85%. Furthermore the design will aim to include more functions like a possibility to identify the content, ways to secure the M-box and better ergonomic handling which are core functions of the whole PI idea (see Table 5).

4. Virtual proof of concept of logistics with M-boxes

To verify the concept of the PI and the assumptions made in MODULUSHCA several virtual tests are planned and already done (virtual proofs VP in second and third part from overall proof, see Figure 10). Regarding to the large number of possible different demonstrations fields and the limited work-capacity in the project two different test areas are highlighted in this chapter: Virtual tests of the M-box functionalities and virtual tests of the SC concept.

4.1. Proof of M-box functionalities

The virtual proof of concept of the M-box functionality is an important and integrally step to minimize design iterations, further costs and therefore duration of development. As shown in chapter 3.2.2 a very broad approach was chosen to address all the requirements of the SC scenarios and to reach the goal to develop a functional solution that performs in reality. Therefore various methods like CAD, CAE and Rapid Prototyping (RP) support the methodical engineering process (shown in Figure 13).

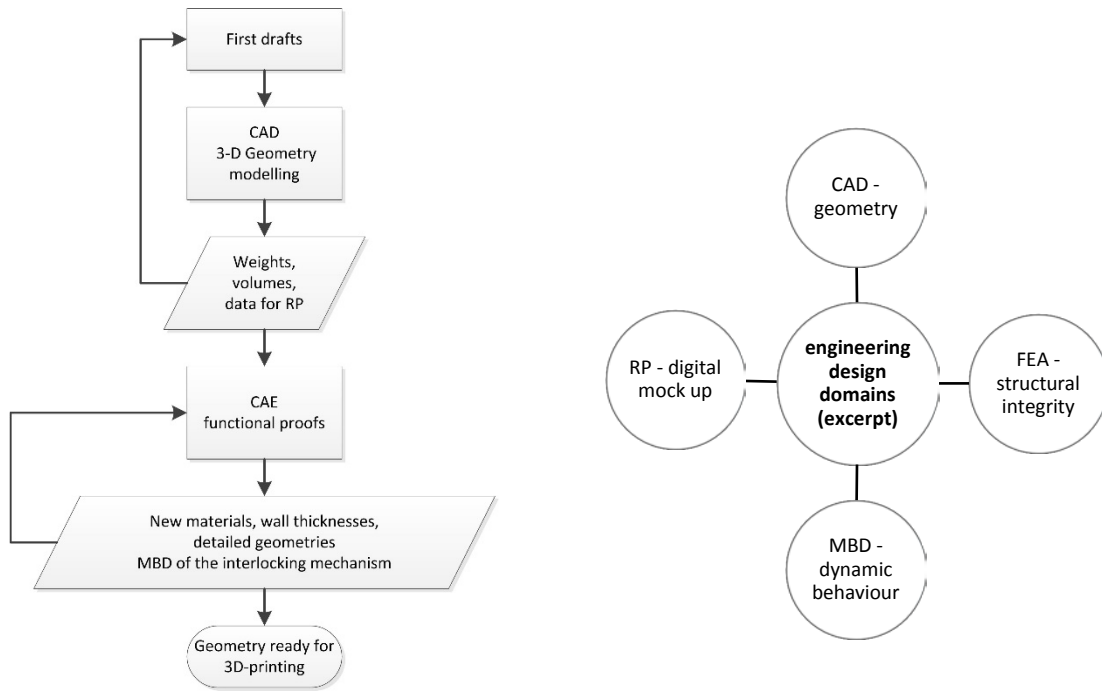


Figure 13: Virtual development process and engineering tools

Due to the iteration after each important development step the virtual proof of concept is ensured for each defined relevant function and its engineered realization. In particular two important virtual test scenarios are identified and investigated in detail:

- Structural stability of the M-box in criss-cross packing pattern in the unit load
- Design optimization for the interlocking system

Structural analysis with Finite Element methods (FEM for Finite Elements-analyses FEA) and Multi-body dynamics (MBD) calculations are used to model and simulate the behaviour of the M-box virtually. After the first development step the structural strength of the M-box has to be proved via FEA. This is the first proof of concept in the engineering process and provides decisions about the material choices and other design details to guarantee the required stiffness and strength of the M-box. As outlined in chapter 3.2.2 the assumed scenario is that the box is loaded with double the payload and the unit load is built in criss-cross pattern with boxes of the same size and weight.

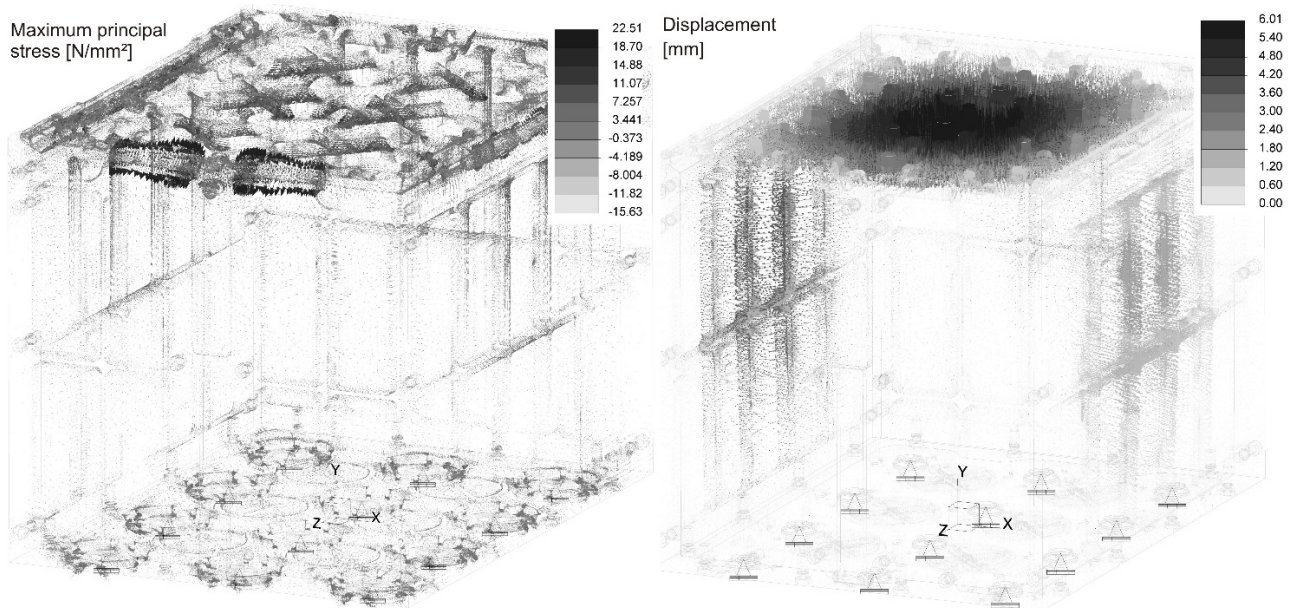


Figure 14: Results of M-box's FEA

Figure 14 shows the maximum principal stress and displacement of the M-box with the described boundaries. The results prove obviously that the materials choices and design details are optimized to cope with the maximum load as required in [20]. For the interlocking mechanism, multi-body-dynamics analyses are carried out to calculate the load on specific components of the mechanism in different scenarios during its lifetime. This step is necessary to reach adequate dimensioning of the design parts according to the appearing loads. This leads to minimization of space, secure operation and reduction of wear.

4.2. M-box SC scenario proof

For the virtual proof of concept of the SC scenario the current situation has to be compared with the future MODULUSHCA scenario. Therefore the PI scenario has to be simulated based on the current shipping data to get an honest illustration of the future scenario. The aim of this is to show the impact of the M-box sizes and the number of used M-box types on the number of necessary trailers to ship the goods with M-boxes. To transfer the current situation virtually to the PI scenario the method outlined in Figure 15 is used [3]:

- 1) Based on the shipment data of project partner P&G, 709 trailer are identified which ship goods now. This number of trailers is the reference to compare the M-box scenario with.
- 2) The monthly shipped items in these trailers are identified.
- 3) For each of these items, the best fitting M-box dimension out of the available sizes gets determined. The items in an M-box were $\pm 25\%$ the number of items allowed in the current case. This process gets done with a computerized algorithm [6], [7].
- 4) The number and type of the used M-boxes and also their specifications like weight and centre of mass are now known. Based on this data, the unit loads can be built. As mentioned in chapter 3.2.2, each unit load is built out of one M-box type with one type of product inside. This means a unit load is built out of always the same M-boxes with the same items in it and due to the modularity and the structural stability of the M-boxes, the utilisation of the unit loads is always 100% (see Table 6)
- 5) The stability of the unit loads is calculated (see chapter 3.2.2) to assure that the unit loads can be shipped practically. Afterwards these unit loads get distributed to trailers to calculate the number of necessary trailers. For this purpose the developed Bin Packing Algorithm (chapter 3.2.2) is used. The last step of this virtual proof of concept is to place the unit loads on the trailers so that restrictions of law (e.g.: maximum and minimum axis load, etc.) and „physics“ (e.g.: desired centre of mass on trailer, etc.) are respected. For this purpose the Balanced Trailer Load Algorithm finds a possible solution under the restriction of these constraints (chapter 3.2.2).
- 6) After this step the 709 trailers which are used in the current situation can be compared to the number of trailers in the future by using the M-boxes. Note that today the 709 trailers run from the plant to different locations. In the PI, the trailers would be shipped from the plant to a PI-Hub and then consolidation will be used along a point-to-point hub network.

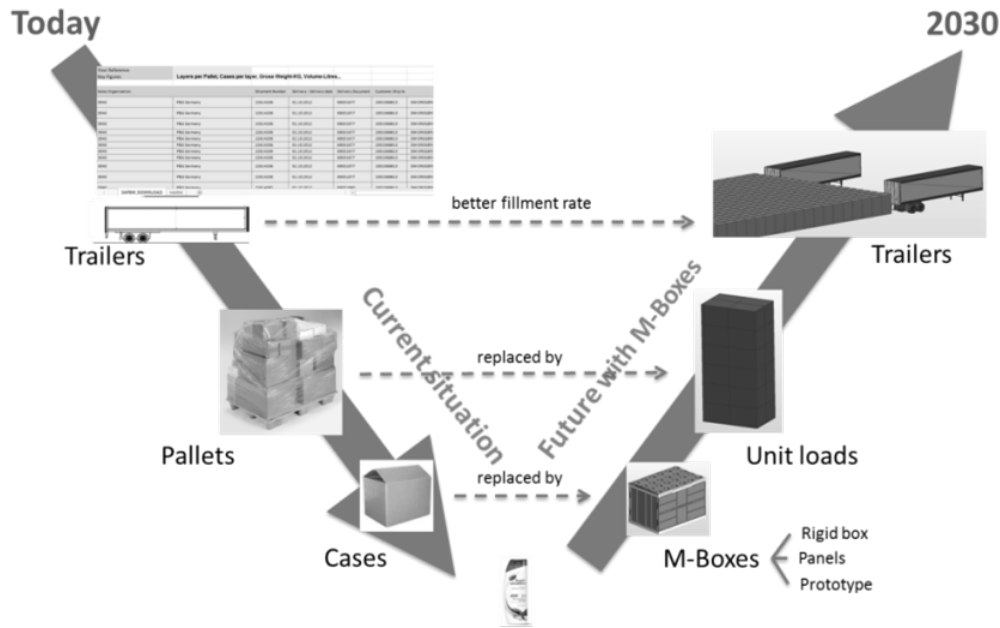


Figure 15: Virtual proof of concept method for the SC

The results of the experiment illustrate the dilemma in the current logistics system based on carton-based containments where the product is required to provide much of the structural integrity of the unit load. Actually nearly full carton cases of products (above 85% with nearly unlimited range of carton case sizes) lead to only 70% full unit loads, because stapling carton boxes doesn't allow same maximum heights than with M-boxes. This instance and the derived requirements of the SC lead to the results of the virtual proof of concept and can be summarized (see Table 6): This 81% full unit loads, with a much smaller number of box sizes than actual carton case sizes, can be seen as an achievement of the whole MODULUSHCA idea, beside the 22,5% less trailers.

Table 6: truck fullness results [3]

	Item utilisation of the M-Box's volume	M-Box utilisation of the unit loads volume	Item utilisation of the unit load	Number of trailers used	Difference to the current situation
5 M-Boxes	56%	100%	56%	745	+5%
9 M-Boxes	63%	100%	63%	652	-8%
Full Set (155 out of 440)	81%	100%	81%	549	-22,5%

The truck fullness and M-box utilisation depends strongly on the number of used box sizes. This leads to the fact that the number of used trailers significantly decreases (about 22%) with the full set of used M-boxes. Modelling the Key Performance Indicators and solutions for operational interconnectivity in FMCG has shown that the whole SC must be taken into account. Handling costs are the major part of logistics costs. The use of M-boxes is then very useful for reducing handling costs and a more efficient way to ship goods. The cost impacts, benefits or on-costs of the M-box solutions will be driven not only by improvements enabled by better vehicle utilisation, but also by improvements in unit, case and load handling efficiency and physical storage [19] (further informations on cost benefits see [19]).

5. M-box-vision for 2030 - outlook

The PI aims to bring maximum flexibility and interconnectivity to the SC and the M-boxes are a key element of this intention. Starting the design process it was obvious that the gap between the SCs in the PI-vision and the SC system today will lead to two fundamentally different ways to build and design a modular box:

- 1) Rigid boxes – as described in chapter 3.4
- 2) Boxes built out of panels:
 Panels means modular panels which can be used as a top-, bottom- or side panel with no limitation to orientation. Using such modular panels will allow building many different boxes and using less different panels (an example is outlined in Figure 16) and will so bring more flexibility to the SC-system.

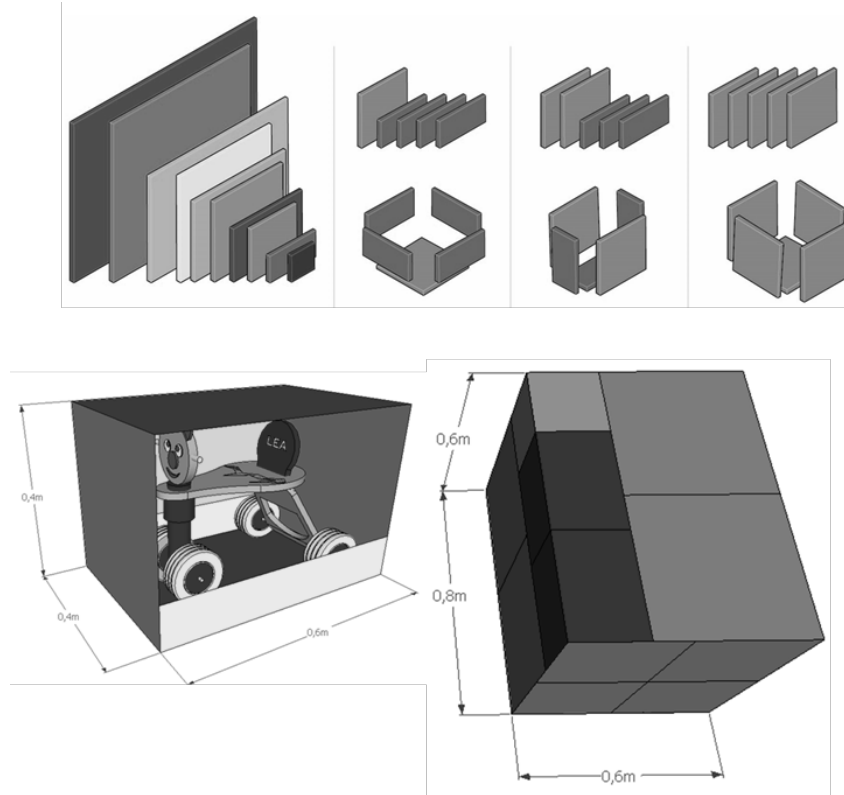


Figure 16: M-box built out of modular panels [4]

This future scenario, allowing many different rigid boxes or detachable boxes built out of panels in the SCs, can raise doubts about the efficiency and feasibility of pooling so many different boxes or parts and can lead to logistics and financial problems and obstacles. Challenges to overcome will be:

- In the complexities of the modern SC keeping components together will be a huge logistical challenge
- As soon as a part of a product is detached it is at a risk of being lost and also damaged
- A successful pooling business is based on having the right product available at the right location at the right time
- One way to overcome this would be to budget the additional costs in oversupplying the network to overcome the risk of component shortage

As the PI-Initiative and the MODULUSHCA concept aim to change the whole SC and the way it works, the consortium strongly believes that these obstacles are manageable in the future. Therefore one of the tasks within the MODULUSHCA project will be to further develop the innovative concept of modular boxes built out of modular panels.

6. Practical proof of concept – outlook [21]

The first “physical” test run will take place in a closed inter-site SC of one of the consortium partner’s customisation centre. In this first logistics pilot, the developed M-boxes will replace pallets and cases that are currently used for the intra/inter-site transportation. The aim is to scale this up to an open interconnected network beyond the company boundaries at later stage accomplishing the scope of this project. The pilot will consist on introducing some M-boxes into the current flow of goods of a company evaluating and monitoring the impact that the new system will have on people safety, product security (decreased damage and traceability), processes and information flows. The M-boxes will be assessed against the following KPIs:

- Ergonomics (weight, grip handle)

- Quality assurance (cleanability, package and product damage)
- Safety (fire protection)
- Others

and should demonstrate value creation capabilities. An Inter-site Transportation Pilot will be performed in order to validate vehicle loading optimization, stackability, stability, 24" drop test, shaker table, inclined conveyor, or even ISTA 3E standard for shipping of full product pallets.

The second "physical" test run will use one of the consortium partner's distribution networks. It will demonstrate the handling of the new information formats as well as analyses the handling M-boxes in the transshipment processes, together with testing the sensor system and communication device (not part of this article, see [24]) that will be developed. The demonstration will make an effort to integrate and test the algorithm about collaborative scheduling and routing for interconnected logistics. This tests use an existing physical and/or digital infrastructure of a logistics service provider. Special interest will be the operational fulfilment of the reversed logistics (empty packaging and returned goods) during normal deliveries. Optimizations in combining reversed logistics with operational deliveries could prove efficient deployment of the modular container. This will be performed in order to validate the KPI's of handling, (un-) loading, reversed logistics, traceability, utilization of truck capacity, stackability and robustness

Initially the project group expects increased load efficiency thanks to the interconnectibility of the M-boxes, allowing better space utilization in storage and in transport. Once the M-boxes will become a standard there will be even more efficiencies as the FMCG companies will naturally converge towards Products and Packages designs that maximize the weight and volume fill of the boxes themselves. The main benefits out of the test runs in a closed inter-site SC demonstration and in distribution networks are:

- Greatly reduced amount of carton versus what is in use today
- Increased load efficiency
- Improved both safety and security issues all along the SC
- Increase of load efficiency; use of available box/trailer capacity
- Overall decrease of the transport kilometres and reduction of CO₂
- Improved handling during loading and unloading
- Reversed logistics vs. operational deliveries
- Tracability

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9. Appendix

Table 7: List of essential requirements for the M-box [2]

Nr.	desired M-box functionality
1	Fully foldable/collapsible by one operator to the smallest size possible
2	The M-box must fully encapsulate the product
3	The box must allow access to the product without the need to detach any components via at least two foldable doors/sides
4	The units must be designed to integrate and interlock such that smaller units can be used to build larger units. Combining two units should take an operator 1-2 movements
5	Different sizes of the M-box should be compatible to stack with each other (in open state only, not folded) in a non-handed lateral orientation
6	The process of combining/stacking units must be suitable for both a manual and automated operation
7	Folded boxes must be easy to distinguish for type/size
8	The M-box must allow the fitment of industry standard dunnage to provide product protection
9	The M-box must be converted between open and closed states within 2- 3 movements
10	The M-box must have a passive track & trace system that can geographically cover the complete network, including international coverage
11	The M-box must incorporate an identification feature – bar code or label
12	The M-box must be able to be folded and opened/closed by means of an automated system
13	M-box must provide the means to identify the contents without opening the unit
14	The unit must be capable of being handled by all standard automated handling equipment, including but not limited to, chain, roller, belt and gravity-fed conveyors
15	Folded units must withstand a compression load calculated as ((3.7m divided by height of each unit) x weight of each unit x safety factor of 2) kg
16	Open units must safely hold product with density of up to 500Kg/m ³ in all operating scenarios
17	Open units must withstand a compression load calculated as ((3.7m divided by height of each unit) x 18Kg x safety factor of 2) kg
18	If the box is of a size to be handled manually it should be rated at a maximum 17kg
19	Weight of the product should be as low as possible and suitable for manual handling
20	Must be stable in an operating environment of -20degC to +40degC
21	Must be fully resistant to absorbing moisture
22	Must be free from any water or dirt-traps
23	Exposed areas must be resistant to attack by common industrial and household chemicals (including cleaning agents, aerosols, gasoline etc.)
24	Must not be affected by UV light
25	Overall damage rate is very important and the box must be extremely durable in normal usage, being highly resistant to damage
26	The box must be designed with a minimum expected service life of 10 years
27	The box must conform to the relevant ISTA 7B criteria
28	The unit must be easy to clean through washing with regular mains water
29	The design must encourage a quick drying process

30	The unit must have some degree of reparability - the ability to replace/repair damaged components without having to replace the complete unit
31	Must be designed for safe manual handling – no sharp edges, finger traps etc.
32	Folding/collapsing and erection operations must require acceptable levels of force and be free from any possible risk of injury
33	Fire retardant or performance is not relevant unless the product is to be used in the US
34	Unique developments and features that can be subjected to IP protection will be considered as advantageous
35	The pallet must be compliant with the EU packaging legislation 1994/62/EC and updated directive 2004/12/EC. Special attention is to be given to article 11 and 22 related to the maximum allowed concentration levels of heavy metals
36	The M-box must provide means by which it can be secured within a truck/trailer when a) folded b) loaded
37	The M-box must be compatible with standard wheeled dollies
38	The M-box must be stable when stored open or folded up to a height of 3.5m
39	The M-box should be designed for internal storage
40	high perceived quality throughout the life of the product is highly desirable
41	Colour – the product must be able to be produced in different colours
42	The product is designed to prioritise use within Europe, but must be suitable for US and Asia-Pacific applications
43	100% of product should be subjected to a visual inspection prior to re-use, including, but not limited to Track & Trace technology, cleanliness, damage and functionality