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Integrated product development and lifecycle management in building production – A case study for logistic of mortar distribution in building sites

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ABSTRACT

In this work, there was developed a modular container based on the principle of integrated product development (IPD), as a device to facilitate the distribution of mortar between workplaces during the production of a multi-story building, as part of the IPD strategy applied to a project under development. Such a project deals with the distribution of mortar to perform activities that use it. Since IPD is a strategy that encompasses several factors and agents, whose primary aim is to maximize the total quality of a product, all lifecycle of a product development aims to minimize risks of security, of use, economics, and markets. Implementing the IPD in buildings is complex, and many times during the development process, there is necessary to develop tools and artifacts to improve the process itself. The IPD diagnosed the distribution of the mortar as a critical task in the building process. Here is presented one solution adopted by the IPD design team to improve the transportation logistics of mortar, according to the product of lifecycle management (PLM) in the production of buildings. The device created following the same criteria of the global project in its development since it should meet the product IPD and meet the specific criteria of its future production. Then, by applying finite element analysis, throughout its development, it was possible to reduce the amount of welding, cut plates, and estimated time for its production. Forward, the design PLM was satisfactorily fulfilled for the device, and the global project, once it completes the design of the device, the integrated development of the production and distribution of the mortar was realized.

1. Introduction

In developing countries, earthquakes are not affected, which multi-story buildings are almost entirely in a concrete structure, with external and internal closure with concrete or ceramic blocks. Thus, the use of mortars of various types is intensive in working floors, and they have two sources: produced in the construction site, or industrialized and supplied for use.

Mortars produced outside the execution site avoid some problems related to inventory area, production area, management of inputs used to produce them, transportation, and management of human resources for the entire production and logistics process linked to this activity. Mortars produced on-site are usually available on time and quantities required for use but consume energy, storage space, and risk of loss of perishable raw material (cement). Besides, it requires human resources for the entire activity cycle.

The lack of integration between product design projects, the layout of the production site, and significant production cause several problems related to logistics, deficiency in the supply, coordination, and planning during production [1]. However, in Brazil, the percentage of mortar produced ‘on the spot’ is still much higher than the use of industrialized mortars.

Implementing the principle of integrated product development in the production of buildings, at first, may seem unfeasible. However, as long as the IPD team can have the autonomy to perform all the activities, bringing together all the agents involved, from customers to marketing services, it is possible to develop the building product within this principle.

Fig. 1 resumes the brief evolution of the product development products from the industrial revolution in the 1800s, up to the XXI century, with remarkable exponential evolution after the 2nd war, and next with the use of the personal computers and their evolution for applying in manufacturing industries. Therefore, many theories and concepts were possible to develop themselves after processing an extensive amount of data after the 2000s, which can be named as the digital era in many senses.

The device presented meets the IPD as part of a simulation of execution of the activity of production and distribution of mortars for...
the fourth floor of a building composed of 19 type floors and 425 m² per floor. This simulation was performed to understand the mechanisms and variables involving the tasks associated with the activity and the agents involved. The interactions were performed as part of the IPD, during the production phase.

The project is considered completed when the planned phases in the IPD are ultimately concluded, according to the aims proposed by the development team. These phases are numbered as critical points and can be named as product idealization, IPD team forming (IPDT), interactions with suppliers, market and customers, definition and acquisition of the area (for a factory or building site), preparation of projects and their definitions for production. Also, the post-production and delivery phases for use must be defined, be approved by IPDT, and be possible to be managed by the product lifetime management team (PLM).

The premises described were necessary to isolate the variables belonging to the predecessor and predecessor activities of those belonging to the analyzed activity, allowing it to focus on the selected activity, to study proposed scenarios, and verify the consequences in its modifications.

While the project developed, several critical points were observed, which should change to provide the improvement of the entire production process. However, the main one was the form of distribution and use of mortars, which could only have substantial improvement if the form of distribution underwent changes in the process and technology used for its distribution and use.

In this work, the intention was not to discuss more in-depth the fundamentals or how to promote the implementation of IPD as a product development strategy. Instead, the whole project shows the possibility to apply the IPD in construction if the professionals involved would change their vision concerning the real function of buildings, that is, a product that should satisfy the individual and collective housing needs, and not for financial investments.

2. Literature review

2.1. Integrated product development (IPD)

IPD is a framework of principles for product development, which simultaneously integrates the various stages of development, which traditionally followed temporal linearity. It is in organic evolution, and includes in its scope not only the design and manufacturing as early, but includes services, processes, tooling, and various agents, in real-time [1]. Such agents can represent financial groups, people, or companies that have some kind of interest in the product to be developed, produced, delivered, and consumed, or in the problem to be solved.

Through IPD, several principles emerged in the 1980s, as named Product Development Process (PDP) or New Product Development (NPD), which aimed to satisfy the customers through the delivery of products with higher quality, reliability, and safety for using. During the following years, the IPD grew and assimilates other strategies for product development. Among these are Concurrent Engineering (CE), Quality for deployment (QFD), Design for Excellence (DfX) [2,3]. More recently, the Product Lifecycle Management (PLM) was introduced as the management tool for global planning and control of all the integrated phases, as tracker codes followed online, and other resources for controlling all the product lifecycle [4].

As described in item 1, the principle of IPD applied to civil construction is still relatively unknown. Thus, no literature contemplates all development, from the concept to the monitoring of the useful life of the building product, but isolated themes such as supply chain or projects developed with a focus on the consumer [5].

Although the literature does not consider, IPD is not limited to an integrated development process. However, a complex system of creation/active and organic solutions, continually changing and evolving throughout the development of an idea or problem. Thus, it integrates not only people with multidisciplinary knowledge [6] but also...
aggregates sociocultural aspects of the agents involved. Interchanging and using multicultural diversity and the interrelationships between agents and third parties indirectly involved, to reach the final development process, a product or service that is almost fitted to the customers’ group for which it was conceptualized and developed. In this way, it is possible to break unfounded barriers from the professional and governmental community and authorities [7].

One of the fundamental principles in IPD is the capacity to collaborate. Therefore, one of the most crucial procedures during the process is to search the optimum equilibrium between the interest of each agent involved, with full autonomy of the teams. Therefore, not only the knowledge and expertise of their members must be considered. The most important is such that pose changings in traditional psychological and sociocultural concepts to succeed in the entire process [8]. This success refers not only to material success but also to the success of convergence of interests between agents, the success of cohesion and commitment. Only in this way, it is possible to develop, plan, execute, verify, correct, and learn during the process. Such a process is reached through the convergence of ideas, needs, and collective vision internal and external to the team, to develop the whole product or service [8,9].

The IPD can be analogous to a conical spiral, in which at each step there is a joint evolution and a focal closure, in which ideas and advances occur in uninterrupted brain-storms between those involved in a project, adhering people, tools, and process, according to the complexity of the development [1].

First, the moderator defines the development strategies with each team responsible for some part of the development. This definition must be done in the development phase of the project. Next, during the process, the moderator must define them for production, use, or destination to the end of service life. Each team is formed by a team leader and one member of each knowledge necessary to conduct a particular phase of the product development flow.

2.2. Product lifecycle management (PLM)

PLM is a set of management methods that act in a continuous and crossed flow during the various phases through which a product passes. It starts with product designing lifecycle management (PLCD), such as the first lifecycle. Next, it iteratively propagates to management in two parts: the first consisting of the production site (PLCP) lifecycle and the second by the production lifecycle of the designed and defined product or service [10]. The third phase takes place from the management of logistics and delivery of the product for use or consumption. Finally, following the end of the product life, the device move on to the management of the life cycle of reuse, disposal, or reconversion, as defined by the IPD [11], and concepts applied simultaneously, whose management became possible with the advent of integrated management software, in real-time. These tools allow from the initial concept of a product, the integration of internal and external agents under the established IPD planning to manage product development phases properly. Therefore, they were integrated and adequately committed to each other, so that each phase is carried out satisfactorily, with the lowest rate of corrections [12].

During the evolution of IPD, PLM is used to plan, control, and institu- tes the policies and determine the right team leaders responsible by monitoring the evolution of the process through the teams, which, while interacting simultaneously [8–12], while developing the activities of each team, strengthen in parallel to the completion of the PLCD.

In the PLCD, it is possible to predict which points would present critical problems, and which interventions in the project must be performed to avoid them through the virtual factory tool. The virtual factory creates reality in the current context IPD time and generates several scenarios, with the alternatives provided by planning, control, and forecasting from the PLM. Thus, all aspects involving IPD-production are virtualized and changed to analyze the probable positive and negative consequences and allow decisions to be made assertively. Then, after the decisions taken about the scenarios, the production lifecycle (PLCP) begins. In this phase, new planning variables are integrated into the PLM [8,12], involving suppliers of inputs and equipment, transporters, human resources, among others, to define the production guidelines according to what was defined in the predecessor phase by the IPD [8].

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![Fig. 2. Key points of the IPD process framework.](image-url)


According to the complexity of the product design, the process of production, the raw materials needed, and the human resources available in all the phases of the IPD, the team leader must adopt more or fewer teams and subjects to consider for each IPD phase. Such subjects may be: planning the delivery of services and materials, quality and expertise required of the team members, contracts with suppliers, human resources of the production line, and others, concerning a particular product or service in development.

The team leader coordinates each lifecycle, and he must predict all the procedures to solve issues related to the post product lifecycle use (PLCU).

Despite its complexity and few barriers to implementation, PLM has several advantages, such as the rational use of resources, reduction of losses by the improvement of processes and materials, and global and punctual integration of the agents involved in product development [8, 12,13].

Fig. 2 shows the IPD evolutionary flow, with the critical points concerning the integrated lifecycles, since the conception up to the lifecycle of disposal, reuse, conversion, or recycling after the product’s end of life.

The conical spring is the path in which the pitch represents the evolution. In contrast, each turn represents the interactions and iterations that are occurring during the decisions taken along the evolutionary flow.

In this work, one of the IPD phases is much concerned with the logistics that is implicit to the activities in the building sector. However, it is necessary to study logistics in construction sites using fresh approaches, and several studies show the importance of integrating processing (or conversion), transportation, waiting, and inspection activities to add value to the final product [13–16].
2.3. Design for manufacturing (DfMA)

Design for manufacturing (DfM) and design for assembly (DfA) are design methods based on the DfX set of design strategies with one or more targets to reach. Such a methodology of design emerged in the mid-1980s, as part of other competitive business strategies, arising before implementing total quality ISO standardization [17]. These strategies were initially developed to improve the competitiveness of companies with products tailored to the needs of the market. However, DfX scopes expanded through years, to sectors other than industrial production, and today, many production sectors are more or less connected when developing the DfX, according to the product or service and its function in society.

Both principles follow a logical pattern; because the DfM is the predecessor of the DfA [18]. Therefore, the two principles can be combined to create a new one: Design for Manufacture and Assembly (DfMA) [19], which covers the two design principles simultaneously, i.e., the product development team must consider the manufacturability and assembly ability of a product, during the entire designing process. Thus, the DfMA aims at designing easy-to-manufacture multifunctional components and reducing the use of fastening components and unnecessary adjustments [13,18–21], whereas PLM deals with lifecycle management.

Issues concerning manufacturing and assembly—namely, the performance and durability of a product or optimization of topology and geometry—are solved by the design teams using computational tools [22].

Nowadays, the market offers many tools used to develop and manage the designing and manufacturing processes. Few of them are the 3DEXPERIENCE–PLM®, ARAS Soft®, and SIEMENS Teamcenter® PLM. Such tools can offer computational support to develop a product using the principles mentioned above, have the agility for designing manufacturing processes; this may help in improving the ability of different teams working on product development to reach their desired goals [23,24].

3. Tools and methods

3.1. Tools

The following tools were used in this study for device design:

a. A computational tool for Parasolid modeling and finite element analysis- SolidWorks® 2019 [22].
b. Workstation with a 3600 MHz Xeon® processor and two interconnected graphics cards for GPU processing, and 32 GB RAM.

c. A workstation with a 3.60 GHz Intel Xeon® processor and 32 GB RAM.

3.2. Methods

Fig. 3 shows the schematic flow followed in this work, regarding the phase of the IPD considered developing the device. The shadowed activities in Fig. 3 are the phases of the IPD and PLM that were considered as defined to develop the device’s production design through the DfMA. These activities interactions (shadow arrows) are defined before the container’s development. They revealed that mortar distribution plays a vital role during the production lifecycle. However, the traditional loading and transportation methods proved to be inefficient in solving the issues concerning the reduction of time, waste of material, and use of human resources adequately. To solve these issues, only with equipment other than usual will be necessary.

All the IPD teams interacting to find a better solution concerning the geometry, the best material, the fabrication process, the energetic and logistical costs. Next, the teams chose the supplier, which can produce the device into the required time to deliver the tool or device in a building site.

Through the PLCD team, all issues are discussed and solved between the teams in real-time through the computational PLM platform. The results give the feedback to the IPD teams, and they make the decisions based on the arrows showed in Fig. 3. Since the arrows point in two directions, the procedure has two possible actions: “DO” or “DO NOT,” according to the requirements of the global IPD, i.e., the building IPD. After the decisions, the PLCD team is responsible for conducting the evolution or reconfiguration.

The PLM computational tool was used in the study conducted for the activity of production and transportation of mortar. As a result, the device was modified to reach such requirements.

The critical requirements defined by the IPD team were the total volume to deliver at the same time in the workplace, the width of the module to pass through the doors opening, the lifecycle of the device.

The maneuverability was verified to preserve the health of the operator during the transportation process throughout the pavement. However, it is a study under development concerning human health factors by the IPD team during building development.

The container should be manufactured without complex parts, should be modular, and robust concerning the work environment, and should not react with the materials it transports to comply with the DfMA requirements.

During each phase of development, for instance, regarding the dimensions, the DfX team reported to the PLCD team, which had all the requirements made by the IPD team for the general product development (building) and the device’s development itself. Such procedures can only be efficient if computational tools are used for general monitoring of processes in real-time. In this way, teams can decide with less likelihood of error, immediately after any advance, or modification, in the product under development.

The macro distribution of design and modeling of the MAPC may be discretized in:

a. Concept development based on IPD requirements (cost, durability, ergonomics, disability, security, environment, recycling, reuse, manufacturing, assembling, disassembling, reconversion, interaction);

b. Design evolution to production lifecycle, simultaneously to the modifications needed the dimensional adjustments, materials used, fabrication process, and others referred to the lifecycle of future use;

c. Production prediction (machinery, tools, factory plant, facilities, and economic aspects);

d. Product lifecycle evaluation before the production (revision of all requirements and simulate the component or assembly, according to actual conditions of operation/use, a warranty extension and limitations);

e. Real-time corrections, modifications, fixes, and approvals;

f. Production and delivery for consumption or use.

3.2.1. MAPC design development

The Parasolid model of the modular anti-overflow palleterized container (MAPC) device was developed based on the DfM method according to the IPD and PLM, as described in 3 and 3.2.

To satisfy design requirements was developed different conceptual models until to reach a satisfactory evolutionary level in terms of load capacity, production procedure, coupling and decoupling, and transport, according to the procedure described in 3.2.

First, a sequence of three models was designed to solve issues concerning the follow IPD requirements:

1. Geometry and volume defined for the capacity of 0.3 m³;

2. Total width including transportation car do not exceed 800 mm, to permit pass through the door openings;

3. Each module must have at least one side with a height of 700 mm or less from the top to the base, to allow the operator to handle the mortar or concrete blocks;
4. The MAPC should fit the three modules to allow simultaneous filling, without overflowing or leaking sideways the mortar or other material;
5. Each module must be self-supporting and have supports that block its accidental tipping and serve as spacers for transport;
6. The MAPC should be painted with sturdy paint and cardboard holder to allow visual identification;
7. The MAPC should be transported by manual palletized cargo carts, already available on the market.
8. The manufacture of MAPC can be carried out by any size of the company, provided that the manufacturer has the conditions to produce it strictly following the design requirements.

Based on the previous IPD requirements, the project was iteratively developed and approved by the PLCD team at each stage to proceed with
the subsequent phase until its completion.

At the end of the first step of the DFMA, production planning began, which comprised determining how the MAPC would be manufactured. After decisions on locations, suppliers, and available equipment, it was defined that the manufacturing process would be by cutting, cold forming, and welding.

The final design and the sequence of assembly of the MAPC were divided into two types: central module (CM) and extremity module (EM). The difference between the two types of modules is at the EM side 01 height (Fig. 4a), the C of the CM (Fig. 4b), and the EM flange A, about the angle B of the CM.

A lower side is needed to connect the three modules, and to permit the operator to handle the material deposited on the bottom of all modules. During loading at the mortar production plant, it is unnecessary to move the MAPC to fill all the modules because of the inner lower board profile, where the material passes through between the modules.

Fig. 4a shows the exploded sequence of assembling the EM, with the body (01), the two sides (02), the angles for reinforcement (03), the cylindrical support, and the protection plate (04 and 05), the feet bodies and bases (06 and 07).

The numerical sequence of welding occurs in parallel:

Piece 05 welded in 04 and piece 07 welded in 06, while piece 02 welded in 01, piece 03 in 01. Then pieces 04 and 05 welded in 02, and finally, pieces 06 and 07 welded in 01.

The identical procedure was done for the module CM shown in Fig. 4c. The main body of the modules is the only part that has a difference of cut and conformation, and of total dimension developed. All other parts (02-07) are replications of those shown in Fig. 4a.

The next step of the DFMA was to detail the production sequence, and determine the arrangement of the cuts on the standard steel plate, measuring 3000 mm long by 1500 wide. If a large industry would produce the MAPC, roll changes the plates with the same width and length 50 m or 100 m. Therefore, concerning the arrangement of the pieces over the sheets does not modify. Thus, the cutting plans were developed to provide the maximum useful width of the steel sheet, and two different arrangements were planned. Fig. 4c shows the cutting of the EM body and smaller pieces, while Fig. 4d the cutting of the CM body and four flanged laterals.

The complete MAPC design with all the modules is shown in Fig. 5, where the transportation locker between them is visible too.

3.2.2. Finite element analysis (FEA)

Before starting FEA, it was necessary to demarcate a plane, as shown in Fig. 6, to establish the limit to be considered by the hydrostatic pressure in the model since the higher sides should not influence the mortar mass inside the modules.

The boundary condition of the theoretical calculations was used for simulating the hydrostatic load; here, the hydrostatic pressure was zero at the upper surface of the liquid and maximum at the lower surface (varying linearly) [25,26].

Finite element analysis (FEA) was conducted based on the modeling results, and it was changing according to the feedback of the IPD team to the PLCD concerning the requirements described in 3.

FEA can evaluate any product or structure developed or modeled, and it assumes that if element \( e \) exhibits elastic behavior, it can be represented by the following relationship,

\[
4q^e = K^e a^e + f_n^e + f_n^a \tag{1}
\]

where \( q^e \) is the elemental matrix of nodal forces acting on element \( e \), \( a^e \) is the elemental displacement matrix on the same element, and \( K^e \) is the elemental square stiffness matrix. It can assume any dimension [25]. \( K^e \) can be defined as follows,
where each matrix item is a square submatrix of $\mathbf{K}$ and can assume the form $l \times l$, in which $l$ is the number of components acting in each node of the element. $f_{i}^{0}$ is the nodal forces required to balance the distributed force, and $\varepsilon_{i}^{f}$ is the strains acting on the element, respectively [27]. Therefore, according to the principle of energy conservation, it is possible to define the sum of non-zero forces acting on node $i$ of a given element ($r_{i}$) as:

$$r_{i} = \left( \sum_{e=1}^{n} K_{e}^{i} \right) a_{i} + \left( \sum_{e=1}^{n} K_{e}^{f} \right) a_{i} + \sum_{e=1}^{n} f_{i}^{f}$$  \hspace{1cm} (3)$$

where $f_{i}^{f}$ represents the forces acting on the element: $f_{i}^{f} = f_{i}^{\alpha} + f_{i}^{0}$, and $a_{i}$ represents nodal displacement. It is possible to generate a generalized relationship for all the elements in the matrix using the relationship shown in (4) [27].

$$K a = r + f$$  \hspace{1cm} (4)$$

In these equations, $K_{e}$ and $f_{i}$ are generalized sub-matrices used in FEA for propagating the summation of actions, strains, and displacements on the whole component using the mesh created based on (4).

When the FEA tool considers the tridimensional element, with known external applied forces, and internal forces caused by body equilibrium, virtual work, initial stress, and initial strain, the general equation is given by (7) [27, 28],

$$\sigma = D(\varepsilon - \varepsilon_{0}) + \sigma_{0}$$  \hspace{1cm} (7)$$

where $\varepsilon$ and $\varepsilon_{0}$ are the final and initial strains, respectively, $\sigma$ and $\sigma_{0}$ are the final and initial stresses, respectively, and $D$ is the elasticity matrix of isotropic material. It can be represented as shown in (8),

$$D = \frac{E}{1 - \nu^{2}} \begin{pmatrix} 1 & \nu & 0 \\ \nu & 1 & 0 \\ 0 & 0 & (1 - \nu)/2 \end{pmatrix}$$  \hspace{1cm} (8)$$

where $E$ is the elastic modulus of the material being considered, and $\nu$ is its Poisson’s coefficient. According to Hooke’s law, $\varepsilon = F/EA$, where $F$ is the force, $E$ represents the elastic modulus, and $A$ is the area of the element. However, because FEA tests the dynamic iterations between each result, the strain $\varepsilon$ is given by the derivative of the displacement gradient.

The tensorial product of the intrinsic components of vector displacement is given by $u_{a,b} = u_{a}\delta_{ab} + u_{b}\delta_{ab}$ where the subscripts $a$ and $b$ indicate the directions of the Cartesian axes, $u$ is the vector in one or more of the Cartesian directions and defines the displacement gradient. The instantaneous strain tensor is given by (9),

$$\varepsilon = \nabla\mathbf{u}^{(S)} = \frac{1}{2} \left[ \nabla\mathbf{u} - \left( \nabla\mathbf{u} \right)^{T} \right]$$  \hspace{1cm} (9a)$$

where the superscript $s$ and $T$ represent the symmetric part and transpose of the displacement gradient of $u$, respectively. The displacement gradient tensor $\nabla\mathbf{u}$ is given by (10) [28]:

$$\nabla\mathbf{u} = u_{a}\delta_{ab} \otimes \mathbf{i}_{b}$$  \hspace{1cm} (10)$$

where $\mathbf{i}_{a}$ and $\mathbf{i}_{b}$ are the vectors considered in the plane.

The fatigue analysis, through the FEA, is a powerful tool to support the product development and to predict the behavior of the constitutive materials of a component or product. Such evaluation depends on the knowledge of many parameters, like the welding material, the microstructure of grains, and others, as mentioned in literature [29-31].

There are innumerable approaches to evaluate the fatigue, from which, for metallic alloys, the most applied in FEA are: the Goodman [31], the Soderberg [32], the Smith [33], Watson, and Topper - SWT [34], and more recently, the ASME [34]. Each one can predict the low or high cycle of fatigue, depending on the application and material nature.

In this work the method to estimate the $S$–$N$ curve was based on [34], since the model can apply different coefficients for low or high cycle fatigue estimation, as (11),

$$S_{\text{avg}} = S_{\text{max}} + S_{a} \quad \text{for } S_{\text{max}} > 0$$  \hspace{1cm} (11)$$

where $S_{\text{avg}}$ is the fully reversed stress amplitude, $S_{\text{max}}$ and $S_{a}$ are the maximum predictable stress, and the stress amplitude, respectively.

In simulated process was used for the stress amplitude ($S_{\text{avg}}$), a modified SWT average approach, proposed by Rajad and Sonsino [35], where there is no present the fully reversed stress amplitude ($S_{\text{mnp}}$). Therefore, a factor parameter $M$ is used to compensate the stress, if there is no present one of the extreme stress values, for tensile or compression:

![Coordinate System and Mesh Detail](image-url)
\[ M = \frac{S_e, R = 1 - S_e, R = 0}{S_e, R = 0} \] (12)

where \( S_e, R = 1 \) and \( S_e, R = 0 \) are the stress fatigue level for fully reversed loading (\( R = -1 \)), and the stress fatigue level with pulsed stress from zero to the estimated limit (\( R = 0 \)), respectively. Further, for the particular case of this work, with \( 0 \leq R \) or \( S_m > S_a \) (where \( S_m \) is the mean stress), the average stress is given by Refs. [35]:

\[ S_{avg, R = 0} = \frac{S_m + M \times S_e}{M + 1} \] (13)

The correlations are shown in (12) and (13) are useful for the case where fatigue life prediction of weldments is necessary, and thus, is used only the nominal stress amplitude, without the mean stress corrections [36].

At the beginning of the FEA, the first step is to input the galvanized steel alloy selected [36, 37] and the welding filament [36] into the Parasolid model before pre-processing; the input parameters are:

- Elastic modulus \( E = 2 \times 10^5 \text{ N/mm}^2 \) [36]
- Poisson’s ratio \( \nu = 0.26 \) [36].
- Shear modulus \( G = 7.85 \times 10^4 \text{ N/mm}^2 \) [36]
- Specific mass: \( 7.87 \times 10^{-2} \text{ g/mm}^3 \) [36]
- Tensile strength \( \sigma_{T, Rd} = 3.47 \times 10^2 \text{ N/mm}^2 \) [36]
- Compression strength \( \sigma_{C, Rd} = 3.47 \times 10^2 \text{ N/mm}^2 \) [36]
- The density of the mortar used to fill the container \( \rho = 2.2 \times 10^{-6} \text{ kg/mm}^3 \)
- Acceleration due to gravity \( g = 9.81 \text{ m/s}^2 \)
- Welding filament tensile strength \( \sigma_{Tw} = 4.21 \text{ N/mm}^2 \) [38]
- Welding filament compression strength \( \sigma_{Cw} = 4.1 \text{ N/mm}^2 \) [38]
- Welding filament Poisson’s ratio \( \nu = 0.29 \) [38]
- Design lifetime requirement = 7.5 years

For the simplification of the linear hydrostatic loading, the equation \( P_h = g \rho b d^2 dh \), was used to calculate the normal load. In this equation, when \( h = 0 \), then \( P_h = 0 \), when \( h = k \), \( P_h = g \rho b k \), where: \( 0 \leq k \leq h \), and \( gd = 1.962 \times 10^{-2} \text{ N}, \) which varies linearly regarding height. Thus, for \( h = 1000 \text{ mm} \), \( P_h = 19.62 \text{ MPa} \).

Pressure calculated using the equations above was used as inputs alongside other properties for pre-processing, which included the loading and constraints and the mesh of the CM (Fig. 7 (a) and (b)) and the same for the MAPC (Fig. 9 (a) and (b)) assembled.

A solid mesh with a maximum size of 20 mm and a minimum size of 2 mm was used to ensure adequate quality for proper verification. A total of 92,881 nodes and 46,490 elements were created for the TA model according to the premises defined by the boundary conditions, and the mesh is curvature-based, with 16 Jacobian points per element. Further, owing to the complexity and differences between the shell and plate, when one dimension was much smaller than the others, tetrahedral elements were used (Fig. 7 (b)).

Similarly to the CM, a mesh with 413,455 nodes and 216,471 elements was created for the MAPC using the same boundary conditions, as shown in Fig. 8a and b.

4. Results and discussion

After approval of the production design by the IPD team, the PLM team leader assigns the team to analyze the MAPC about the strength and the minimum lifecycle of five years, predicted for the time of the overall development of the building product. Therefore, If the MAPC
design does not meet the IPD requirements, it should be reformulated.

### 4.1. FEA results

During the FEA post-processing, the von Mises failure criterion approach was adopted to calculate stresses and strains in the developed models considering the maximum strength in the global coordinate system, as shown in Fig. 9a.

Fig. 9(b)–(d) are the corresponding strains along X, Y, and Z axes, respectively.

The FEA results for the considered input parameters of gravity, hydrostatic pressure, and mortar density showed that the maximum stress was 65.6 N/mm². Further, the most significant strain of 3.16e⁻⁴ mm/mm occurred along the Y-axis, representing elongation along the horizontal edge that connected the two adjacent plates shown in Fig. 9c.

Following Hooke’s law of elasticity, the simulated strains in direction 1 and 2 (Fig. 9b and c) reached $\varepsilon_{12} = \frac{\varepsilon_2}{\varepsilon_1} = 0.25$, which is 3.1% lower than the Poisson’s ratio of the galvanized steel considered as the device’s material; thus, there is no substantial difference between the real Poisson’s ratio with the one found in the simulation.

According to the standards and literature [24, 25, 33-39], $S_d \leq \sigma_R$, where $S_d$ is the total load on the element, and $\sigma_R$ is the characteristic resistance of the material.

For the steel material used in FEA, the following relation is considered,

$$S_d \leq \sigma_R, \quad \sigma_R = \sum_{i=1}^{n} \gamma_i \sigma_{R_i},$$  \hspace{1cm} (14)

where $\gamma_i$ represents the coefficients of reduction of the material strength, according to the classes of chemical, environmental and operational aggressiveness, to which the device will be subject.

After multiplying characteristic material strength, $\sigma_{TC, Rd}$ by the strength reduction coefficients, where the first concerning to self-load
plus the quasi-static load ($\gamma_1 = 0.85$), the second to the environmental aggressiveness ($\gamma_2 = 0.9$), and the third corresponding to cyclic loading ($\gamma_3 = 0.8$), the strength was found to be 212.2 MPa.

Regarding the welding material, the same expression (14) is used, and the resumed results were found to be 210.4 MPa. The resulted strength of the weldment material to be lower than the steel plate material is explainable by the coefficient of reduction due to the stress concentration on welded points [36,37,39].

Because the results obtained through the triaxial approach referred to the stress tensors, where the maximum stress level was not restricted to the principal axes, the FEA evaluated the object in all directions to find the tensor corresponding to the maximum stress. These results were compared with the von Mises failure criterion. Subsequently, an identical analysis was conducted to evaluate the strains in three directions, which were not coincident with the principal axes X, Y, and Z.

Fig. 10a–d show the results achieved using the triaxial failure criterion.

In the triaxial’s case failure criterion, the maximum stress was found to be 111 MPa, which was ~69% greater than the value calculated using the von Mises criterion. However, even though the stress and the safety factor results were lesser than the maximum allowable strength for the steel alloy considered in FEA material. Similarly, the maximal strain observed during the triaxial analysis occurred in the first principal direction ($3.47 \times 10^{-4}$ mm/mm) as compared to the Y-axis in the von Mises criterion ($3.16 \times 10^{-4}$ mm/mm).

Using Euler’s relationship regarding the critical pressure acting on an element and assuming that both extremities of a compressed column are the relation fixed-free, the following relationship for the critical stress is formulated [39],

$$P_c = \frac{\pi^2 EI}{(KL)^2} = \frac{\pi^2 ES}{L^2}$$

(9b)

where $\sigma_c$ is the critical buckling stress, $E$ is the elastic modulus of the material, $S$ is the cross-sectional area of the element verified, where the width considered is $b = 100$ mm $\times$ plate thickness, $h = 3$ mm, thus, $S = 300$ mm$^2$, for the angled bottom of the MAPC.

The slenderness ($\lambda$), which is the effective length, $L = 1000$ mm, divided by the least radius of gyration, which is defined by $r = (I \div A)^{0.5}$, is equal to 0.866 mm. Solving (9), $\sigma_c = 466.9$ MPa, and such stress are nearly four times larger than the maximum triaxial stress found through the FEA (111 MPa). Therefore, the higher lateral of the EM body reached lower buckling stress than critical buckling regarding standard requirements [39].

The position of maximum strain in Fig. 9c indicates contraction owing to the localized compression stress along X-axis. Comparing the triaxial and von Mises results, in absolute values, it is observed that the maximum strain corresponding to the former was ~11% greater than that of the latter. Furthermore, it should be understood that because the strain represents compression, it should be accounted for when investigating local bending.

As showed in Fig. 10c, the strain in E2 represents a transverse deflection of the steel plate, due to the internal hydrostatic pressure of the considered material (fresh mortar), which is not linear along with the height of the plate. Fig. 11 can explain such behavior, where the compared results achieved through the FEA, for the triaxial and von Mises stresses are shown.

The comparison of the curves Stress-strain (S–S), there is used the orthonormal direction "Y" from von Mises, with the direction E2, from the triaxial analysis. In such a case, the E2 direction was theoretically coincident with the "Y" direction, unless few variations presented in the plotted S–S curve. Such variations may reflect the non-linearity of the stress caused by the variable hydrostatic pressure along with the height of the container.

In triaxial stress, there is an intermediate-range of loading, where the strain is higher than the von Mises stress, up to 37 MPa, approximately. Next, while the loading increases, the strain rate presents a small increment. This behavior goes up to the 45.5 MPa level when the strain rate decreases slowly to converge to the von Mises strain at the end of the simulation.

4.2. Operational lifecycle prediction

Finally, to estimate the serviceable life of the container materials (steel plates and welding), there was simulated the damage level and life prediction for the cyclical loading case, which was 1200 s, or 20 min.

All data used in this prediction are partial outputs from the global IPD of the building, as described in 3. The time was computed to empty the container, while the operator used the mortar. Finally, the time to move the container from the floor was computed, until its return to the starting task point. These were: 0.5 min for container loading, 2.5 min for horizontal and vertical transportation, and 5 in maximum static load. Then, the mortar is continuously retired from the container up to complete the cycle [36], as shown schematically in Fig. 12.

Fig. 12 represents the time to complete one cycle of 20 min (min). The codes $L_1$ and $L_2$ are the initial and final time for loading the container (0–0.5 min), while the $H_1$ and $V_1$ are the codes for time to start the horizontal and vertical travels along with the building (1–3.5 min). The codes $H_2$ and $V_1$ are the finish time of the first travel, while the $H_2$ and $H_3$ ones are the time to start the travel two along the floor where the mortar is used (3.5–5 min). Finally, the codes $H_3$ and $V_2$ and $H_3$ are the times to start the returning travel, horizontally and vertically, and then arriving at the start point, respectively (15–20 min).

Two low cycles of fatigue are present in the simulation. The first cycle is the loading-transportation and unloading-transportation, and the second cycle is the number of working days. Once the device is used
a few hours a day along the year, a reduction coefficient for cyclical loading \( (\gamma_3 = 0.8) \) was used [39]. Therefore, to take into account the average working-day of 8 h, each day has 24 cycles, and considering the total average of working-days in Brazil as 300 days, the total of cycles during the year is 7200.

Fig. 13 shows the reached critical point of limit life of 111 MPa, for the simulated triaxial stress, where the weld joint fails, according to the fatigue FEA. Such a value is between \( 7.0 \times 10^{-4} \)–\( 7.8 \times 10^{-4} \) cycles, and thus, the available time of the container is \( S_a = 7.4 \times 10^{-4} \) divided by \( 7.2 \times 10^{-3} \) cycles per year, equal to 10.27 years, which is 40% greater than the design lifetime.

The lifetime results agree with the resulted S–N stress-life curve for the galvanized steel, which agrees with such given by the ASME [36,37], as shown in Fig. 14, which was low-cycle fatigue during long cycles of loading and unloading, as noticed in Fig. 13.

The pointed maximum in Fig. 14 concerns the jointing between the board fold with the vertical edge where the piece flanged lateral (shown in Fig. 4) was welded in the EM body. Hence, the angle formed by the lap presents high tension concentration for the other regions. Then, it was considered as the critical point subjected to damage propagation along with the device’s life in the fatigue FEA. However, these issues may occur over the design lifetime predicted (7.5 years), according to the fatigue analysis.

Throughout the designing product development of the IPD with the management, controlling of the design steps and evolution through the PLM up to simulate the required scenario, the device’s design reached the quality and durability predicted, according to the time for concluding the whole product (building) that is five years.

5. Conclusions

In summary, a modular device was developed for transporting different materials in industrial sites following the principles of IPD, using as methodologies the DfX and PLM. Once the aim was to deliver a product with a life that could cover the global product/service development, i.e., improve the mortar distribution in building working floors, the MAPC design reached the requirements imposed by IPD, through the PLCD team.

Concerning the fatigue, the FEA results showed that the materials and the operational conditions predicted for the device are satisfactory, and no maintenance was considered during the lifetime. The fatigue analysis gave a predictable life superior to the production lifecycle of the building, which is desirable for equipment and tools.

Although MAPC was not used in the production of any building until the culmination of this study, six units would employ them in the production of a building with 25 stories. The worldwide health crisis caused by COVID-19 has destroyed all long-term planning of entrepreneurs and developers.

The design progress followed the successor task after validation of the predecessors by the IPD teams during the project described in Fig. 3. Next, the evolution and results converged to the PLCD requirements. However, a prototype should be tested in terms of its producibility and their usability in building sites.

Credit author statement

The following credits represent the contribution of each author of the manuscript submitted:
Paulo C. Duarte Jr.: Conceptualization, Writing – Original draft, Visualization, Methodology, Formal analysis, Validation, Investigation, Software.

Fernando Nakao: Patenting process, Formal analysis, Software.

Alitiano Ortenzi Conceptualization, Writing – Review & Editing, Supervisor, Project administrator.

Ethical statements

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There are no conflicts of interest to declare.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Once we not secure about how extensive this declaration is, we inserted the information below:

Few details did not appear in the manuscript due to patenting process protection. However, there is no other issues that could be considered as potential competing interests.

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Appendix A. Supplementary data

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Corrigendum to ‘Integrated product development and lifecycle management in building production – A case study for logistic of mortar distribution in building sites’ [J. Build. Eng. 32 (2020) 101802]

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The authors regret Equation (8) on page eight has the follow format, with brackets in the matrix, rather such appeared in published version:

\[ D = \frac{E}{1 - \nu^2} \begin{bmatrix} 1 & \nu & 0 \\ \nu & 1 & 0 \\ 0 & 0 & (1 - \nu)/2 \end{bmatrix} \] (8)

Equation (11) in the page eight, has the follow form, with both terms below the square root with power 2.

\[ S_{ar} = \sqrt{S_{max}^2 + S_a^2} \text{ for } S_{max} > 0 \] (11)

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