UNIVERSITY OF UDINE

POLYTECHNIC DEPARTMENT OF ENGINEERING AND ARCHITECTURE

Sustainable Production Planning Optimisation for Project-Based Enterprises

Ph.D. in Environmental and Energy Engineering Science - XXIX Cycle

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Chapter 1

Scope and Overview

The triple bottom line concept (Elkington, 1998) highlights that at the intersection of social, environmental, and economic performance there are activities that result in long-term economic benefits and competitive advantage for the firm. Logistics offers great opportunity of recognizing such activities, leading to sustainable supply chain management. Optimization of sustainable supply networks for Project Based Enterprises (PBEs), in which the core business is represented by the development of projects where innovation and planning have to cohabit in order to reach high innovation and sustainability levels without neglecting the control on the efficiency dimension, has not deserved great attention in literature. In fact, make to stock manufacturing can benefit from the research literature on production planning and organization through the application of the largely developed concept of Economic Order Quantity and the principles of lean throughout the entire supply chain, while in the construction industry production planning has been investigated in the field of the precast.

Even if precast elements have to feed site requirements and the molds in most of the cases are custom-made, these models cannot be used for PBEs, since precast production has large similarities to the manufacturing production, due to the fact that the units to produce (e.g. columns, beams and slabs) are necessary to the concrete building and structural elements which are obtained by molds usage at a centralized plant and then transported to the building site for the assembly phase. In PBEs, every project has different scopes, the work-flow is transient, multiple crafts are involved, projects are planned and carried on in short time frames and there is a multitude of material and equipment projected for installation. As a consequence, different trade-off among the design, procurement, production, and installation requirements can arise for each project and should be properly managed.

The aim of this work is to present a new model to integrate the complex features characterizing the building construction industry by finding the best compromise to meet departments different needs, hence interbreeding social, environmental and economic aspects to enhance long-term performances. The program wants to be useful to gain the most coherent to project specifications mid-term production plan and to be a decision support tool by answering the following questions:

- which elements to be assembled and shipped every week?
- which is the best contractual agreement for the project?
- which storage capacity should be equipped at the production plant and installation site?
- how much overtime should we consider to make the project feasible?
- which is the loss forecast of the project due to contractual, production and logistics issues?

In this thesis the model has been applied to a worldwide leading company of the Curtain Wall sector, *Permasteelisa Group*, which is an excellence operating in the North East of Italy and that gave the availability to suitable interviews, data analysis, production reports, project specifications and contractual intents.

Research

The PBE production planning problem has been modeled and solved by Constraint Programming (CP). The main advantage for adopting CP relies on the unlimited type of relations between variables that a modeler can adopt to describe the desired properties of the solutions and the objective to be pursued. Moreover, as compared with techniques such as genetic algorithms, simulated annealing and tabu search, constraint-based systems are usually easier to modify and maintain due to the separation of the modeling phase from the solving one, which allows to easily add or remove constraints while preserving the main structure of the model. This flexibility can be particularly useful in the case of PBE's, where each project can present peculiarities to be inserted into the general production planning model.

We coded and solved the model using the Comet package, which provides an object-oriented language with a number of innovative modeling and control abstractions, while embedding the best algorithms and the best search strategies developed by the CP research community. The best sustainable solution is identified by assigning a cost to feasible solutions. Four main components have been introduced in order to foster sustainable solutions:

1. the cost of poor utilization of the assembly line;
2. the cost wasted in set-ups;

3. the cost of poor utilization of the containers' space;

4. capital costs for stock immobilization.

The cost of poor utilization of the assembly line is calculated taking into account the learning-forgetting phenomenon typical of the limited productions in PBEs: workers improve their performances according to the production sequence, which combines the several product typologies by matching the contractual milestones. In the learning phase, which lasts as long as the same typology is being assembled in the production batch, the efficiency is going to improve, while, on the contrary, it is going to slow down each time there is a break.

This concept allows to embrace the social dimension of sustainability and allows to obtain:

- time feasible and reliable production schedules, in order to meet contractual handover dates;

- accurate project production cost valuing;

- working-stress reducing by considering the actual capacity and efficiency of workers, thus obtaining a friendly environment.

The reference learning-forgetting model is the one by Jaber M.Y. (1996), whose goodness has been proven by empirical evidences carried out thanks to the data gathered from Permasteelisa Group, a worldwide leading Contractor in the engineering, project management, manufacturing and installation of architectural envelops and interior systems. Production data belonging to three different projects of curtain wall have been analyzed in order to find out concrete evidence of the learning and forgetting phenomenon applicability.

A suitable new methodology in order to reach the goal is being proposed in this study, by basing on the production data achieved from the information system of the company and the technical/organizational directions given by people working at the production and tender departments. Interviews have been held with the production manager, the logistic manager and the tender leader of the three projects that have been taken into account and their opitions have been collected and interbred to build the following technique. As an evidence, the phenomenon occurs in all of the project product families, so that the learning curve associated to each of them has been drawn.

Further, a set of numerical examples that show how the model of Jaber M.Y. (1996) behaves under a variety of forgetting breaks and different values of the learning constant, obtained from the previous empirical research have been performed. As an outcome, the total production time calculated through the model is always higher than the one simply evaluated as the multiplying of the tender standard time by the quantity to produce. The lack of consideration of the learning-forgetting phenomenon in the production planning is misleading since the production time is under-estimated up to 69%, with negative consequences on the actual planning in terms of time and capacity on the assembly line, causing delays on the general Project Plan. This misalignment increases with the number of stops on the assembly line since the benefits that comes from the learning effect exploiting is limited by the forgetting phase and a potential expression that explicates this relationship has been achieved.

The second cost introduced in this thesis model aims at minimizing the cost for set-ups, since in PBEs, productions cost related may be significant: due to the huge and varying dimensions of the panels, the automatic conveyor width of the assembly line must be revised several occasions. These kind of activity can take at least 4 hours to be ended, thus causing rather a long unproductive impact.

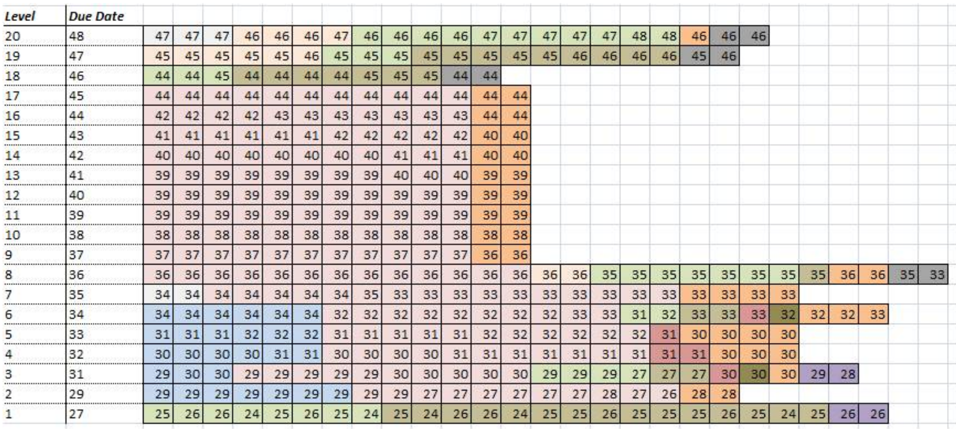
The environmental dimension of sustainability is taken into account by fostering full truck loading, so that less travels are required to the construction plant, with related reduction of GHG emissions from fossil fuel combustion. The lost space in mean of transports, is estimated by assuming that each part type can be associated with a unit load class: this means that elements of different part types can be stacked during transport only if they belong to the same class. Since packs have huge dimensions, number of packs that can be stacked onto each other and number of columns inside the mean of transports can be easily calculated, thus lost space is evaluated as a percentage of the volume of the mean of transport.

The considered cost in the sustainable solution is the one that gives evidence to all of the hidden costs of capital immobilization, which are strongly connected to the contractual payment agreement with the client. The capital cost associated to the unproduction of the line is calculated by considering that the idle time of the assembly line prevents the company for being paid for the production of the units that could have been assembled if the operators would not have stopped. By following the same logic, inventory cost in production and at site can be thought as the postponement payment by the client because of unshipping and uninstalling a certain number of square meters.

Main Results

The model presented in chapter 4 has been applied to Manchester One Spinningfields Building a curtain wall project awarded by Permasteelisa Group and whose learning-forgetting analysis has been previously performed.

For the first 5 weeks of planning in the basic configuration, the major cost item is due to set-ups (45%), followed by overtime (19%), capital costs (18%) and finally less-than-truck load transports (18%). As an evidence, in the basic configuration the pattern of the model is to minimize as much as



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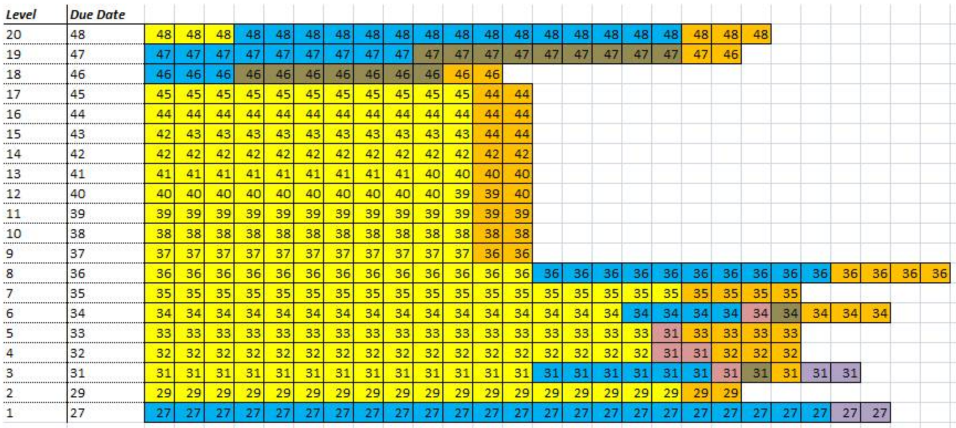
(a) Production planning.



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(b) Shipment planning.

Figure 1.1. Production planning for first horizon in basic configuration.

possible the unproduction of the assembly line and the storage at installation site and the learning-forgetting phenomenon is taken into account in several occasions through the anticipation of the production of item belonging to the same family product. The full production planning of the basic configuration is reported in figure 1.1a, where the packs containing the curtain wall of the building are represented by cells coloured as per product family; the number inside each cell or pack is the production week suggested by the model.

The shipment plan, shown in figure 1.1b, where different colours indicate different crate and so different loading-mode, takes into account the best trade off between truck load optimizing, stock at the production plant and stock at site.

Several simulations have been performed to assess the deviations from the basic configurations:

- at the changing of the contract type;
- at the changing of the importance of the various step (i.e. procurement, production, shipment, installation) in the project scope of work;
- at the decision of the firm to pay more attention at the environmental aspect by reducing the number of transports;
- when the learning-forgetting phenomenon is neglected.

Conclusions

By changing contract type, due to different payment modes associated to the project activities, the model can address the firm in the assessment of the best contractual agreement with the client by showing which is the related loss.

With the modification of the weights of the activities, the firm can model the planning according to the contractual scope of work, which, for example, may not include the installation activity.

In the construction market great importance is given to the environmental theme, so the model allows the company to run the project with a greater impact of the transport cost, in order to take into account not only the economic aspect, but also the environmental one.

The simulation dealing with the absence of learning-forgetting phenomenon shows a squeezed planning which is not physically feasible and bearable by the workers, thus giving a misleading support both in terms of time and costs.

Contractors are paying more and more attention to environmental strategy and environmental impact assessment. In this scenario Project Based Enterprises need a model for the decision making on long, mid and short terms is needed. Our model is aimed at finding the best balance between site and production needs in order to enhance the company performances from the social, economic and environmental point of views, by taking into account production loss, set-up and overtime, less-than-truck load transport costs and capital immobilization financial impact. Thanks to the introduction of the learning-forgetting curve, the model presented in this thesis allows to reduce working stress on operators by considering more reliable production planning rates. Moreover decision-making over the mid-term is supported: the company can test, through different simulations, whether it is necessary and/or convenient to pay for a storage area where to stock the units produced in advance on the due date, as well as gathering a resource planning.

The thesis is structured as follows: context and literature overview is offered in chapter 2; the analysis and empirical evidences of the learning-forgetting phenomenon is explicated in chapter 3; the CP model is presented in chapter 4; results and simulations are fully described in chapter 5.

Chapter 2

Research Context

The aim of this introductory chapter is to outline the strategic context in which the thesis has been worked out. Hence, an overview of the objective of this study, Project Based Enterprises (PBEs), is offered. The concept of sustainability has nowadays to be addressed on three levels: economic, social and environmental. Therefore, in the construction field, which is a market characterized by a peculiar complexity, it is necessary to develop a tool that can support firms in both strategic and operative decisions on the projects awarded, in order to be competitive over the short, mid and long-terms. The research proposed here, fills the gap that comes to the surface by analysing the literature on the theme, with a new sustainable production planning model that integrates the several links of PBEs supply chain. In paragraph 2.1 an introduction to sustainable supply chains is proposed, while in 2.1.1 the literature on the specific case of the construction market is reviewed. Finally, in the last subsection, 2.2, there can be appreciated an overview of the curtain wall segment, which represents the case-study analysed in this thesis, thanks to the data obtained from the collaboration with Permasteelisa Group, a worldwide company leader in the development of building envelopes.

2.1 An Introduction to Sustainability

The most commonly widespread and shared definition of sustainability is the one proposed by Brundtland World Commission on Environment and Development in 1987 (UN, 1987), which defines it as *the development that meets the needs of the present without compromising the ability of future generations to meet their needs.* Carter and Easton (2011) suggest to think about sustainability as a three factors commingling: environment, society and economic performances. This perspective is coherent toward the *Triple Bottom Line* (TBL) concept, exposed by Elkington (1998), which states that at the intersection of these three aspects, there are activities to be pursued by organizations, that positively affect the first two items and also turn into long-term competitive advantage and economic benefits for the firm.

As pointed out by Porter and Kramer (2006), logistics offers a great set of activities and initiatives to draw from, so that the development of a *Sustainable* or *Green Logistics* becomes indispensable. In fact, the application of the sustainability concept is becoming a highly relevant issue for Operations Management, therefore *Sustainable Supply Chain Management* (SSCM) and, with a greater focus on environmental issue, *Green Supply Chain Management* (GSCM), have been given particular stress from the international scientific community in the latest decades, as it comes to the surface by recent literature reviews on the theme (Ashby et al., 2012; Seuring, 2013; Winter and Knemeyer, 2013).

Traditional SCM can be considered as *the management of physical, logical and financial flows in networks of intra- and inter-organizational relationships jointly adding value and achieving customer satisfaction* (Mentzer et al., 2001; Stock and Boyer, 2001), even if no agreed definition is accepted (Corominas, 2013). By extension, there is uncertainty and unshared statement for SSCM also; Ahi and Searcy (2013) and Hassini et al. (2012) in their comprehensive review explain it as *the creation of coordinated supply chains through the voluntary integration of economic, environmental and social considerations with key inter-organizational business systems designed to efficiently and effectively manage the material, information and capital flows associated with the procurement, production, and distribution of products or services in order to meet stakeholder requirements and improve the profitability, competitiveness, and resilience of the organization over the short- and long-term.*

In recent years, publications have then moved towards the shaping of supply *networks*, where several organizations, such as suppliers, producers, distributors and retailers are involved through a win-win approach. Mula et al. (2010) classify mathematical programming models for production and transport planning and conclude that there is a need for comprehensive optimization models and tools. Manzini (2012) develops a top-down tool for the effective design, management and control of multi-echelon logistic production-distribution networks, which supports the decision making process on strategic, tactical and operational issues. Daaboul et al. (2014) propose a way to model, simulate and analyse a value network as a decision support system, to overcome the lack of evaluation of the quality of social relationships, the effectiveness and efficiency of communication and information sharing, the satisfaction of the relevant people or groups and also potentially interfaces, misunderstandings. In order to reach the goal, activities/processes, resources, flows, organizations, both operational and tactical decisions, and values have been modelled in one graph along with the casual influences between immaterial information. A major focus on the very first-tier actor of the network is then given by Genovese et al. (2013), that recommend the importance of greening the supplier selection.

2.1.1 SSCM in Construction Industry

Coordination, innovation, reactivity and flexibility between the several SSC phases are fundamental when considering Project Based Enterprises (Toole and Chinowsky, 2013), in which the core business is represented by the development of projects where innovation and planning have to cohabit in order to reach high innovation and sustainability levels without neglecting the control on the efficiency dimension. With reference to the *Project Management*, a *Construction Project* can be defined by adapting the common statement referred to a Project (Tonchia and Nonino, 2013), so, as a set of activities that aim at the handover of a new building to the client within a set period of time on a defined quality system basis, and through limited financial and human resources. When taking into account SSC for PBEs, e.g. facade and curtain wall firms, a scarce literature has been worked out, while a specific research should be addressed because of the difficulties of the scenario which has to be faced by these kind of companies. PBEs, in facts, have to manage huge variety of materials, products and components peculiar to each single project or ongoing advanced project schedule to adapt to client/consultant wishes.

From the environmental point of view, it is acknowledged that construction activity has major impacts on environment: in the UK market it has been estimated that construction can potentially influence 47% of the total UK carbon emissions (HM Government, 2010). Therefore, SSCM in construction has tended to focus on the flow of materials supply to site, since it not only reduces the environmental and social impact but also improves the operational effectiveness through green design, green operations, green manufacturing, green packaging, waste minimization, reverse logistics (Dadhich et al., 2015). Moreover, as reported by Wong et al. (2013) in their study, the sensibility to the theme given by architects and contractors is increasing, so they present a conceptual scheme to understand relationships among organizational culture, carbon reduction drivers and possible strategy adoption.

On top of this, focus on greening the supply chain leads researchers to the proposal of models to assess the sustainability of construction projects, such as the one in Zhang et al. (2014), where the authors conclude that a project's sustainability capability can change due to the impact of various dynamic variables, particularly those relating to technical measures and people's perception. For this reason, as far as construction market is concerned, several studies have been focused on network integration. Fulford and Standing (2014) investigates on the inefficiency caused by the excessive fragmentation in the construction industry together with disparate project management processes and non-standardized information: by reporting three practical cases they conclude there are great differences between construction and manufacturing SC, the main one being that the majority of manufacturing organisations have ongoing processes and relationships, whilst construction organisations, being project based, have short term relationships, one-of-a-kind products and on site production. Love et al. (2004) previously addressed the problem with a qualitative model to improve the relationships between design and production processes; Tennant and Fernie (2014) also encourage and develop fresh perspectives of supply chain management in construction by integrating the actors belonging to the supply chain of PBEs.

As for the intra-firm SSC, in order to embrace the complexity of the system characterizing construction PBEs, a comprehensive approach on the logistics should be addressed with the optimization of production and installation on site or with the decision to have a stocking area supporting the material flows to site. In fact, large-scale inventory reduction in the construction industry is difficult to achieve, but reduction of waste in other areas would seem practical. From the economic perspective, Critical Path Method (CPM) is the primary planning methodology, but not effectively used in day-by-day management of projects. For this reason Seppänen et al. (2014) propose to utilize the location-based management systems (LBMS), which is a method of construction planning and production control that is based on the movement of resources through the job-site by maximizing continuous use of labour and productivity, while reducing waste and risk; moreover, LBMS controlling methods forecast production basing on actual rates rather then the planned ones (used by CPM).

Make to stock manufacturing can benefit from the research literature on production planning and organization through the application of the largely developed concept of Economic Order Quantity and the principles of lean throughout the entire supply chain, while in the construction industry production planning and scheduling has been investigated in the field of the precast. Chan and Hu (2002) present a constraint programming model to optimize the production of the mold where the objective function includes cost of stock, cost of missing delivery dates, cost of adaptation, cost of mold utilization, subject to: mold-element relationship (from one mold there can be obtained several different type of elements), mold production capacity, delivery requirements and inventory stock requirements. Also W.Tharmmaphornphilas and Sareinpithak (2013) are interested in the same field and focus on the production process: mold preparing, concrete mixing and casting, curing, stripping, product finishing and storing. Given a due date, a number of jobs, a number of molds, and a set of mixing formulas, the authors try to determine the job assignment to the molds, the formula assignment to the jobs, and the mold sequence to minimize the product cost while satisfying the due date through mixed integer programming. This latest technique is also used by A.Khalilil et al. (2014) to minimize production costs for the producer by using the minimum mold types (the authors suggest a grouping scheme, too) and the minimum instances of each mold type necessary to produce all building components. The model also attempts to fully utilize each mold's capacity during its life cycle to reduce resource costs; an optimal plan is achieved to satisfy installation demands for prefabricated components by minimizing molds change-overs. A genetic algorithm-based searching technique to maximize precast plant production under the constraint of limited resources is proposed by Leu and Hwang (2000). The issue is solved through the flow shop problem, which is a scheduling problem taking into account m different machines (i.e. processors) and n jobs (i.e. precast panels) that consist in m operations which requires a different machine. The result sought is the minimization of processing time for panel i on processor j under a set process order, a certain resource demand and limit. Major stress on the environmental issue is given by P.Wu and Feng (2014), who qualitatively tried to identify, through a preset questionnaire submitted to production managers and site managers belonging to 17 precasters, the non-value adding activities in precast concrete production that cause low-carbon emissions.

Even if precast elements have to feed site requirements and the molds in most of the cases are custom-made, these models cannot be used for PBEs, since precast production has large similarities to the manufacturing production, due to the fact that the units to produce (e.g. columns, beams and slabs) are necessary to the concrete building and structural elements which are obtained by molds usage at a centralized plant and then transported to the building site for the assembly phase. On the contrary, in PBEs, every project has different scopes, the work-flow is transient, multiple crafts are involved, projects are planned and carried on in short time frames and there is a multitude of material and equipment projected for installation.

Given the complexity of the industry, construction success depends also on the ways in which project participants collaborate and coordinate to strengthen internal synergy and adapt to external changes (Hwang and Do, 2014). For this reason is important to outline the social aspect of the triple bottom line and to fit it into the construction industry, which is characterized by manual production lines dealing with huge and heavy materials, whose handling is delicate and dangerous. Moreover, materials to be assembled are expensive and have great lead time in case of breakages, so that the Project schedule may be seriously mined in terms of contractual deadlines. Hence, employees work in plants where the quality and safety issues are fundamental, by leading to give significance to their welfare. Therefore, a production plan which is coherent towards the feasible limits of workers operating with this premises in order to get friendly, effective and efficient working environments.

Stated all the above, the literature review shows a lack of synoptic view on the economic, environmental and social themes, that, instead, must be given a all-at-once glance to perform Projects with high profitability and that can give the company a competitive and durable advantage. The model presented in this thesis wants to integrate the complex features characterizing the building construction industry by finding the best compromise to meet departments different needs, hence interbreeding social, environmental and economic aspects to enhance long-term performances.

2.2 Case Study: the Curtain Wall Segment

In this thesis a new model for the production planning in construction Project Based Enterprises has been developed by considering the three dimensions of sustainability, and applied to a worldwide leading company of the Curtain Wall sector, *Permasteelisa Group*, which is an excellence operating in the North East of Italy and that gave the availability to suitable interviews, data analysis, production reports, project specifications and contractual intents. Along with the definition of the best sustainable production plan, the model intends to be a decision support tool since the company can test, through different simulations, whether it is necessary and worthy to pay for a storage area where to stock the produced units, as well as gathering a resouce planning and comparing the different contractual forms that an awarded project can be subject to.

Curtain wall envelopes (CW) are defined as thin, usually aluminium framed walls, containing infills of glass, metal panels or thin stone in addition to glazed in window or door openings; refer to picture 2.1 for a schematic understanding. The frame is anchored to the concrete building structure through a bracketry system and does not have any structural function: the wind and gravity loads of the CW are transferred typically at the floor line (Pond et al., 2015). CW is of paramount importance in terms of building performance and is a fundamental architectural element, not only from the aesthetic point of view, but also for a series of factors such as, complexity, materials and finishings, performance and magnitude, and location of the project. The CW procurement process from cradle to grave through design, manufacturing and installation is perceived as a process with many risk factors because of the cost involved, the technical and engineering requirements, and its position on the critical path of projects.

Generally the CW supply chain is composed of many stages which include (Kassem et al., 2012): architectural design, shop drawing, procurement, manufacturing, installation and maintenance. However, there has been significant standardization in the CW industry and there are some multinational organizations that offer standard CW systems from which the stakeholder (i.e. architect, consultant, client) involved can select the CW elements for their projects. While this greatly simplifies the procurement process, such standard elements are just extruded sections of aluminium, which still need to be designed and manufactured. Therefore, even in case of standard pro-

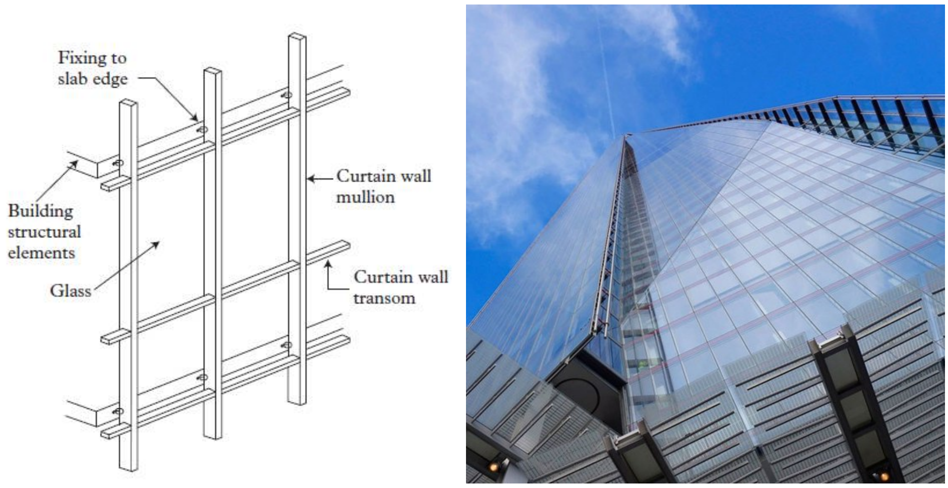


Figure 2.1. Schematic curtain wall (Kassem et al., 2012) and The Shard Building, London.

duct, the management of supply chain of curtain wall is a complex process involving a complex flow of information and materials. The CW units are being pre-fabricated and then transported to site as a unitized frame, normally pre-glazed.

This thesis relies on data offered by Permasteelisa Group, a worldwide leading Contractor in the engineering, project management, manufacturing and installation of architectural envelopes and interior systems. The Group brings its Know-How and expertise to all projects, in particular when dealing with Special Features Buildings, beginning with the design development phases all the way to the successful completion, achieving the customer's expectations. Present in four continents, with a network of around 50 companies in 30 countries and 11 production plants, the Group generates a total turnover of around 1.5 billion euro a year. The mission of the Permasteelisa Group is to design and build innovative and avant-garde architectural works alongside the world's greatest in contemporary architecture, by using advanced technology and eco-sustainable solutions. The ultimate goal is to provide design and construction solutions that meet clients' most varied needs, by working closely with architects and designers from the earliest planning phase (Permasteelisa Group, 2016).

Chapter 3

Learning-Forgetting concept and its applicability

As highlighted by M.Brandenburg et al. (2014) in their literature review, holistic approaches in SSCM that reflect all three sustainability dimensions are relatively rare, even if empirical research shows the growing relevance of multiple sustainability aspects: SSCM research tends to focus primarily on environmental issues, while social facets are widely neglected in empirical and analytical modelling research. In this sense, it is significantly important to take care of the social aspect of the triple bottom line when drawing up the production schedule of a construction project. The setting out of the correct production rate sustainable by workers is fundamental to get:

- time feasible and reliable production schedules, in order to meet contractual handover dates;
- accurate project production cost valuing;
- working-stress reducing by considering the actual capacity and efficiency of workers, thus obtaining a friendly environment.

In the paragraph 3.1 literature on the Learning and Forgetting phenomenon is being analyzed and in paragraph 3.3 Jaber and Bonney's model is presented. This latest has been chosen as the most suitable one to be applied in the production model developed in this research and the empirical proof of this is demonstrated in paragraph 3.4, where real data from three different Permasteelisa Group projects are analyzed in order to shape the best learning curve that actually occurred. Then the importance of the learning-forgetting phenomenon introduction into the project production scheduling model is highlighted in paragraph 3.5, which shows how different production sequencing and different learning curves have impact on production time and rates.

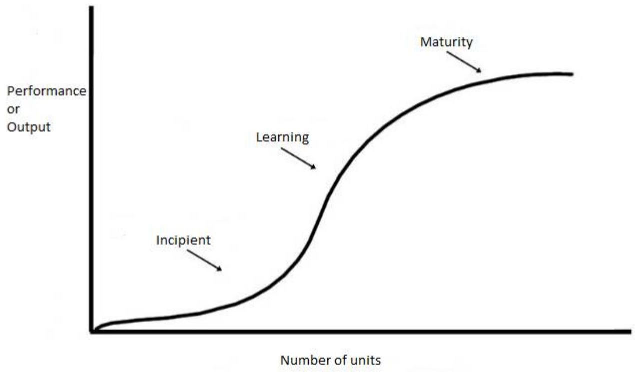


Figure 3.1. The learning life cycle (Carlson and Rowe, 1972).

3.1 The Learning-Forgetting phenomenon: a literature review

A learning curve is a mathematical description of workers' performance in repetitive tasks (Wright, 1936; Teplitz, 1991; Badiru, 1992; L.Argote, 1999; Fioretti, 2007). In fact, Carlson and Rowe (1972) applies the concept of *product life cycles* to tasks, as being described by graph 3.1 and by the following three phases:

1. incipient, where there is just a little improvement and the tasks mainly consist of setup, instructions and tooling;
2. learning, where there is the most improvement and where the *learning phenomena* actually happens; it is characterized by reduction of errors, and time wasting, development of work pattern;
3. maturity, where the production rate becomes asymptotic to the limit.

Several factors can impact on the operators learning performances (Anzanello and Fogliatto, 2011), such as: training programs; workers' motivation in performing tasks; prior experience in the tasks; task complexity. Learning curves are proven to be efficient tools to monitor workers' performances in repetitive tasks, to analyse and control productive operations, to allocate tasks to operators according to their learning profiles, to measure production costs as workers gain experience in a task and to estimate costs of consulting and technology implementation. Here comes the importance of considering such aspect in the production plan of a firm.

3.1.1 Learning Mathematical Models

Learning curves have been firstly developed by Wright (1936), who observed how assembly costs of airplanes reduced with a constant percentage as the production doubles. Since this study has been published, a wide range of mathematical models, both univariate and multivariate, have been researched and extended to several production systems and market segments. Among the univariate, the log-linear, exponential and hyperbolic are widespread. Wright's *log-linear* model expresses a relationship between direct manhours input and cumulative production in the form:

$$T_j = T_1 j^{-l} \tag{3.1}$$

where T_j is the time to produce the j-th unit, j is the production count, T_1 is the theoretical time required to produce the first unit, and parameter l (0 < l <1) the learning slope. Values of l close to 1 denote high learning rate and fast adaption to task execution. Modifications in this model have been carried out to fit specific applications and then recognised as alternative models, one of which is the Standford-B, which incorporates workers' prior experience through parameter B in equation 3.2.

$$T_j = T_1(j + B)^{-l} \tag{3.2}$$

Other models, such as DeJong's and Plateau introduce the influence of machinery in the learning process and idle time due to machinery limitations blocking operators' performance improvement. In addition to these models, others are not so often cited because of their complexity and specific applicability; see Anzanello and Fogliatto (2011) for a full review.

Exponential models present a more complete set of parameters as compared to the log-linear ones, by embodying additional information on workers' learning process, which lead to a more precise estimation of the production rates at the expense of simplicity in application. G.Knecht (1974) merged exponential and log-linear function, by gathering equation 3.3, where c is a second constant and other parameters have been previously defined.

$$T_j = T_1 j^{-l} e^{cj} \tag{3.3}$$

The 3-parameter exponential learning curve is frequently discussed in literature, see equation 3.4, where y indicates the workers' performance in terms of number produced after x units of operation time. The three parameters are: k, which is the maximum workers' performance when the learning process is concluded given as number of items produced per operation time; p which corresponds to workers' prior experience evaluated in time units; r, which is the learning rate also given in time units. A slight modification of this model is offered by the so-called Constant Time, proposed by D.R.Towill (1990), which is also based on operators' previous experience and allows easier estimation of the time required to achieve a certain performance level.

$$y = k(1 - e^{\frac{-(x+p)}{r}}) \tag{3.4}$$

Table 3.1. Comparative analysis of the univariate learning curves.

Author/Name	**Model**	**Equation**	**Nb. of parameters**
Wright	log-linear	$T_j = T_1 j^{-l}$	2
Standford-B	log-linear	$T_j = T_1(j+B)^{-l}$	3
Knecht	exponential	$T_j = T_1 j^{-l} e^{cj}$	3
3-Parameter	exponential	$y = k(1 - e^{\frac{-(x+p)}{r}})$	3
Mazur & Hastie	hyperbolic	$y = k\frac{x}{x+r}$	2

A third category of learning models is the *hyperbolic*, which hosts J.E.Mazur and Hastie (1978), explicated in equation 3.5, where x is the number of conforming units, r is the number of non-conforming units. Hence, y is the percentage of conforming units on the total production, multiplied by a constant k. The same authors also improved this model by adding a new parameter that enables workers' prior experience.

$$y = k\frac{x}{x+r} \tag{3.5}$$

Extensions of the traditional learning curves are provided by *multivariate* curves, which are required when modelling learning scenarios based on two or more independent variables, as displayed in equation 3.6, where K is the performance (cost) to produce the first unit and c_i is the coefficient for the independent variable i (Anzanello and Fogliatto, 2011).

$$C_x = K\prod_{i=1}^{n} c_i x_i^{-l_i} \tag{3.6}$$

Reports on multivariate and its applications are limited in literature, moreover provide significant results on variables' interactions but the presence of non-relevant variables weakens the quality of the model. Hence the use of univariate models is suggested when the effect of additional independent variables on the learning process is uncertain.

A recap of the univariate learning curves presented so far is offered in table 3.1. Log-linears have been applied to several companies, such as: semiconductor industry, electronic and aerospace components manufacturers, chemical industry, automotive parts manufacturers and truck assemblers. In particular, according to literature these models describes most manual operations with acceptable precision offering a non-complex mathematical structure. In addition, R.S.Blancett (2002) applies the model to a building company to evaluate workers' performances in manufacturing. In the light of this, log-linear model best fits the requirement of a PBE, e.g. a curtain wall manufacturer, which is the objective of this thesis.

3.2 Forgetting Phenomenon

Production systems characterized by frequent interruptions, such as the ones of PBEs, have to face the negative effect of the forgetting phenomenon, along with the learning one, as a reduction of the production rate after an inactive period. The forgetting portion of learning cycle can be displayed as a negative decay function, as in graph 3.2. Carlson and Rowe (1972) compare an individual's memory as the equivalent of storing electrical charges in the brain, which implies:

- the initial learning rate is a function of the amount and proximity of prior experience;
- forgetting always happens but the negative effects grows with the interruption length;
- forgetting curves show rapid initial decrease in performance followed by a gradual levelling;
- the rate and amount of forgetting decreases as an increased number of units are completed before interruption occurs.

The forgetting curve relation by Carlson and Rowe (1972) is presented in equation 3.7, where $\hat{T}_x$ is the time for the x-th unit of lost experience of the forgetting curve, x is the amount of output that would have been accumulated if interruption did not occur, $\hat{T}_1$ is the equivalent time for the first unit of the forgetting curve, and f is the forgetting slope.

$$\hat{T}_x = \hat{T}_1 x^f \tag{3.7}$$

This phenomenon has been strongly investigated by Jaber M.Y. (1996), that modelled the forgetting slope using log-linear based curve being dependent on: the learning slope, the quantity produced and the minimum break at which total forgetting occurs. They also show how to determine the value of the forgetting rate once the curve's mathematical formed is assumed, as detailed in paragraph 3.3. This model has then been integrated to quality control techniques in M.Y.Jaber and Givi (2015), where the authors assume forgetting to occur when a worker alternates between the production and the rework segments of a cycle and when cycles are interrupted by production breaks. The result is that the performance of the system improves with faster learning in production and rework, frequent process restorations and transfer of learning between cycles. The impact of forgetting in set-ups and product quality on economic-lot-sizing problem is addressed by M.Y.Jaber and Bonney (2003) with three cost components: set-up cost, holding cost and quality cost. The results indicate that with learning and forgetting in set-up and process quality, the optimal value of the number of lots is pulled

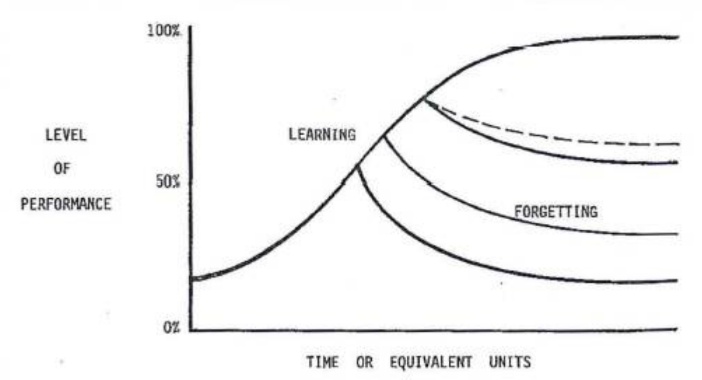


Figure 3.2. Plot of performance versus time (Carlson and Rowe, 1972).

in opposite directions: learning in set-up encourages smaller lots to be produced more frequently, while learning in product quality, encourages larger lots to be produced less frequently.

In this thesis the model by Jaber M.Y. (1996) is being adopted without modifications, since in M.Y.Jaber and Givi (2015) the assumption is that the time to restore the production process is negligible in comparison to the cycle time, which is not the case of a PBE working on external envelops, where, instead, non-conforming units occur when the raw material are not as per design intent causing the complete unproduction of the piece that will be produced when the replacement part will arrive. M.Y.Jaber and Bonney (2003) is also not applicable since the concept of economic-lot-sizing is suitable for make-to-stock productions.

3.3 Production breaks and learning curve

The learning-forgetting curve concept has here been applied to production planning of custom and engineer to order units, departing from the study by Jaber M.Y. (1996), who introduced a model suitable for make to stock manufacturing plants. The author assume the learning curve by Wright (1936) (Eq. 3.1) and the forgetting model by Carlson and Rowe (1972) (Eq. 3.7.

Assume q units are produced in each production run and that interruptions occurs immediately after producing qth unit. In intermittent production runs, there is a gap of sufficient length that some of the learning accumulated in producing q units in the previous lots is not retained when a new run starts up. Hence the production rate at the recommencement would not be as high as when the production ceased. The increase in time to produce the first unit in the next production run depends on the length of the interruption and the time to produce the *qth* unit which is when the

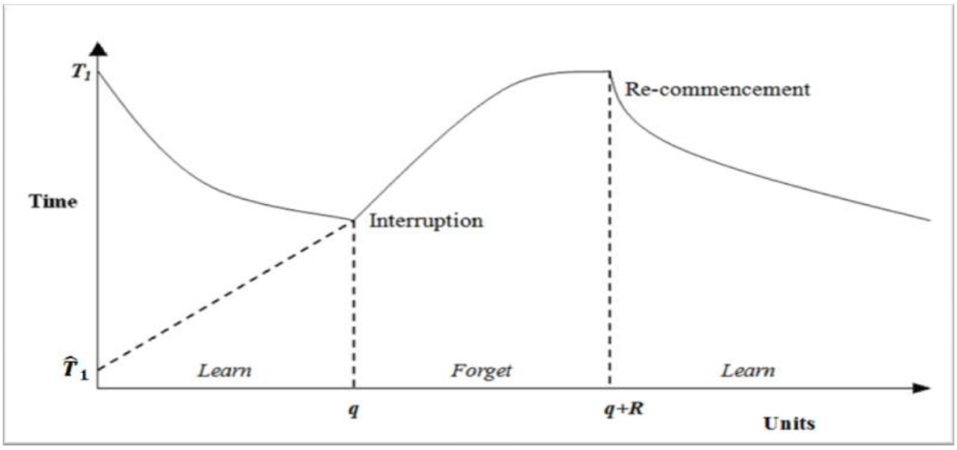


Figure 3.3. The decrease and increase in labour hours due to the learning forgetting effects (Jaber M.Y., 1996).

interruption occurred. This learn-forget-learn relationship is illustrated in figure 3.3, where R is the number of units that would have been produced in time t_B assuming that there had been no break in production. Production on the day production stops in the first cycle is equal to the production on the same day of the first forgetting cycle, that is:

$$T_1 q^{-l} = \hat{T}_1 q^f \tag{3.8}$$

Solving for $\hat{T}_1$ yields:

$$\hat{T}_1 = T_1 q^{-(l+f)} \tag{3.9}$$

Substituting equation 3.9 in 3.8 the time to produce the x-th unit after a lot size of q units is:

$$\hat{T}_x = T_1 q^{-(l+f)} x^f \tag{3.10}$$

If the production is interrupted at lot size $x = q+R$, then solving equation 3.10 for f results in:

$$f = l \frac{\log q}{\log (q+R) - \log q} \tag{3.11}$$

In order to obtain production break length t_B, equation 3.1 has to be integrated over the limits q and $(q+R)$ as shown in equation 3.12, while, similarly, the cumulative time to produce a total of q units is expressed in equation 3.13.

$$t_B = \int_q^{q+R} T_1 y^{-l} dy = \frac{T_1}{1-l}[(q+R)^{1-l} - q^{1-l}] \tag{3.12}$$

$$t_P = \int_0^q T_1 y^{-l} dy = \frac{T_1}{1-l} q^{1-l} \tag{3.13}$$

Solving equation 3.12 for *(q+R)* gives:

$$(q+R) = \left[\frac{1-l}{T_1} t_b + q^{1-l} \right]^{\frac{1}{1-l}} \tag{3.14}$$

This latest equation 3.14 when substituted in 3.13 yields:

$$(q+R) = q[C+1]^{\frac{1}{1-l}} \tag{3.15}$$

$$C = t_B / t_P \tag{3.16}$$

C is explicated in Eq. 3.16 and represents the minimum value of the ratio of the break time to the production time that will achieve total forgetting. If the production process experiences smaller interruption periods, t_b, where $0 < t_b < t_B$, then the time to produce the first unit in the next cycle is greater than the time it took to produce the last unit in the previous cycle but less than the time to produce the first unit in the first cycle. The forgetting slope *f* can be calculated as follows, by introducing equation 3.15 into 3.11:

$$f = l \frac{l(1-l) \log q}{\log (C+1)} \tag{3.17}$$

In equation 3.17, the value of the forgetting slope, *f*, is zero whenever the learning slope, *l*, is either zero or 1. These two extreme cases correspond to when there is no learning involved, then there is nothing to forget, and when a subject improves rapidly, then the forgetting slope is unimportant. The amount, α, of equivalent units of experience at the beginning of a production run after an interruption period of length t_b is found by equating 3.1 to 3.10 and then solving for α, to obtain:

$$\alpha = q^{\frac{l+f}{l}} (q+s)^{-\frac{f}{l}} \tag{3.18}$$

Therefore the time to produce the first unit in the next production batch is:

$$\hat{T}_{q+1} = T_1 [\alpha + 1]^{-l} \tag{3.19}$$

where $s \leq R$ when $t_b \leq t_B$.

Hence, the above described Jaber M.Y. (1996) model can recursively be adopted for every *i*-th cycle by the followings Eqs. 3.20-3.21, where T_i is the cumulative time to produce M_i units after a production break and $T_{1,i}$ is the time for the first unit:

$$T_i = \frac{T_{1,i}}{1-l} M_i^{1-l} \tag{3.20}$$

$$\hat{T}_{1,i+1} = T_{1,i}[\alpha_{i+1} + 1]^{-l} \tag{3.21}$$

As further explained in chapter 4, the model presented in this thesis integrates the previous learning-forgetting curve results, thanks to a preprocessor, which calculates for each potential sequence of learning phases and breaks during the planning horizon the values of α_{i+1} and T_{1i} for each possible q quantities. These values are then passed as input table data to the main model, which selects the proper parameters on the basis of the current value of production variables. For example, in a planning horizon involving n periods, the possible sequences are 2^{n+1}, reflecting absence/presence of production in each period and the chance the part has never been assembled in the previous planning horizons. Corresponding parameters to identify periods of consecutive productions as well as breaks are used by the main model to properly associate learning-forgetting values.

3.4 Learning-Forgetting Phenomenon: Empirical Evidences

In this section real production data taken out from Permasteelisa Group SAP reports are being analyzed in order to find out concrete evidence of the learning and forgetting phenomenon applicability. Three projects, which are representative of the company product mix, have been taken into account. A suitable new methodology in order to reach the goal is being proposed in this study, by basing on the production data achieved from the information system of the company and the technical/organizational directions given by people working at the production and tender departments. Interviews have been held with the production manager, the logistic manager and the tender leader of the three projects that have been taken into account and their opinions have been collected and interbred to build the following technique.

3.4.1 Methodology Building

First step of the analysis is to interpret, evaluate and organize the available data in a significant way, so practically during the very first preliminary stage of the project design process, panels are being grouped by lots according to their geometry: codes i that have similar components and/or dimensions are named under the same product family k, because similar panels correspond to similar production rates, so that the sum of the codes contained in each family is equal to the total number of the units of the entire Project:

Table 3.2. Produced quantity per product family through the weeks

						Week number						
Product family	**...**	**6**	**7**	**8**	**...**	**14**	**15**	**16**	**...**	**29**	**20**	***Total qty***
C1F	...	70	113	36	...	1	58	168	...	146	2	3403
C1W	...	59	9	10	...	10	13	0	...	37	20	782
...	...	...	...	...	...	...	...	...	...	...	...	...
C4A	...	0	0	0	...	0	0	3	...	0	0	55
C4F	...	0	0	45	...	24	18	41	...	0	0	212
Total qty/week	...	129	212	92	...	87	121	231	...	232	158	5295

Table 3.3. Man-hours per week

Week	**...**	**6**	**7**	**8**	**...**	**14**	**15**	**16**	**...**	**29**	**20**	***Total hrs***
Man-hrs	...	1303	1369	1259	...	1182	1062	1336	...	1050	1391	35507

$$Project\ Units = \sum_{i,k} code_{i,k}$$

For each Project, by departing from SAP data reports, tables containing the code of each curtain-wall family, week and production year, number of assembled panels, have been drawn, see table 3.2. The second information that is necessary to get from SAP reports is the number of man-hours worked per week, i.e. table 3.3.

Third step of the process is to calculate from the merging of tables 3.2 and 3.3 how many man-hours per week have been dedicated to the assembly of each family of products, e.g. to get how a total amount of 1336 man-hours that have been worked in week 16 (table 3.3) have been split among all product family assembled during the same week: C1F, C4A, C4F and so on (table 3.2). This point is quite critical, since the total hours per week have been divided according to the *Degree of Difficulty* (*DoD*) respect to the basic configuration of family product. The *DoD* is obtained on the basis of the preliminary evaluation of the family product production rates that has been done during the tender phase of the project, i.e. a forecast of the standard production time which is elaborated during the time horizon that elapses from the bid winning and the technical definition of the executive project details, necessary to start the purchasing and production process of the pieces to produce. *Tender production rate* evaluation is affected by the hardness of the production process, which depends on how many components have to be assembled and on how and with which sequence they have to be installed by workers to create the panel itself, thus having impact on production time. Once tender analysis is finished, the family product characterized by the lowest production time is identified as the *base*, by meaning that its $\text{DoD}_{\text{base},\%}$ is 0%. If more than one family of the project take-off is characterized by the same minimum standard time, then all of these cases are being considered as *base*. Hence, generally speaking, for the k-th family product the DoD can be calculated as:

$$DoD_{k,\%} = 100(\frac{avg\ std\ time_i}{avg\ std\ time_{base}} - 1)$$

It becomes evident that each code i belonging to family k has the same $\mathrm{DoD_{k,\%}}$:

$$\forall i \in k \Rightarrow DoD_{k,\%} \equiv DoD_{i,\%}$$

A family product F1 that has a $\mathrm{DoD_{F1,\%}} = 50\%$ is going to be 1.5 times more complex than the *base* family, then its estimated production time is going to increase with the same percentage. As previously explained, the definition of the DoD is fundamental to the calculation of the average production time rate of each family product. In fact, by taking into account SAP production reports that show quantity produced per family k week by week (table 3.2), each project family product has been *standardized*, that means they have been readjusted on the basis of the family-base product. This standardization procedure consists in calculating in every week w the *Equivalent Base Quantity* (*EBQ*), which is the equivalent quantity of assembled products belonging to the *k-th* family in terms of *base* codes:

$$EBQ_{k,w} = qty_{k,w}(1 + DoD_{k,\%})$$

where $\mathrm{DoD_{k,\%}}$ identifies the degree of difficulty of the *k-th* family respect to the *base family*, e.g. if in one week there have been produced 100 units of F2 family product, with a $\mathrm{DoD_{F2,\%}} = 80\%$, then these 100 units are equivalent to 180 family-base units. The procedure has to be repeated for each family product and production week, so that the total number of codes readjusted is given by:

$$EBQ_{tot,w} = \sum_{k=1}^{M} EBQ_{k,w}$$

where M is the total number of product family of the entire Project. By knowing the man-hours per week (table 3.3) it is now possible to gather the average production time per week per unit $T_{k,w}$ for all of the i-th code belonging to the k-th family product:

$$T_{k,w} = \frac{total\ manhours_w}{EBQ_{tot,w}}(1 + DoD_{k,\%}) \tag{3.22}$$

A summary of the process can be visually gained through picture 3.4, where the blue colour indicates the data input that this procedure needs, while pink element represent the newly developed items to be calculated in order to obtain $T_{k,w}$.

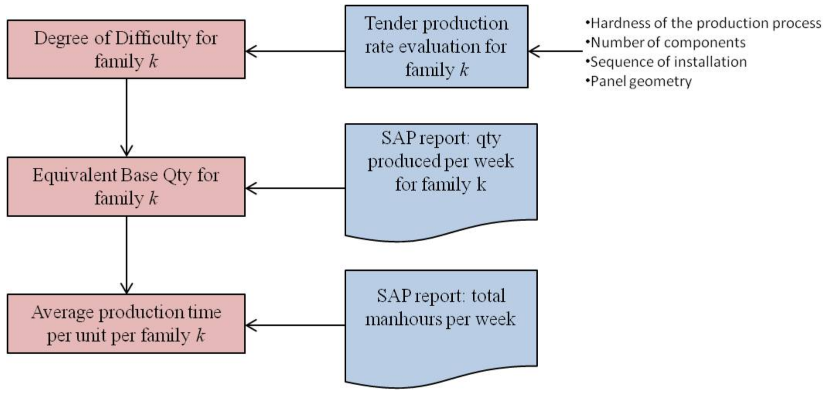


Figure 3.4. Flow chart of the process to calculate $T_{k,w}$, where the blue colour indicates the data input, while pink element represent the newly developed items to be calculated.

Table 3.4. Final Production Project report.

			Week 3			Week 4			Week 5	
$Family_k$	$DoD_{k,\%}$	$qty_{3,k}$	$EBQ_{k,3}$	$T_{k,3}$	$qty_{4,k}$	$EBQ_{k,4}$	$T_{k,4}$	$qty_{5,k}$	$EBQ_{k,5}$	$T_{k,5}$
C1B	70	20	34	15.3	60	102	8.9	43	73.1	7.8
C1V	0	19	19	9.0	6	6	5.2	5	5	4.6
...	...	...	...	...	...	...	...	...	...	...
C5B	20	24	28.8	10.8	16	19.2	6.3	26	31.2	5.5
C1C	115	0	0	-	0	0	-	4	8.56	9.8
$Qty_{k,w}$			**64**			**93**			**103**	
$EBQ_{tot,k}$			**82.8**			**138.2**			**148.1**	
$Manhours_w$			**743.5**			**720.8**			**677.5**	

By proceeding in this way for each family k in each week inside the considered planning horizon, a table such table 3.4 is obtainable; this table is crucial to the plotting of the Wright (1936) learning curve of the Project, Eq. 3.1.

From a preliminary analysis of $T_{k,w}$ in table 3.4 it can be noticed that there is a decreasing trend as the assembled quantity increases through the weeks, so confirming there is a learning phenomenon, which is clearly understandable in family C1B.

It is reasonable to specify that, even if production flow is continue through the horizon, time trend is not always decreasing: for some of the analysed family product the calculated trend increases so that the learning flow seems to stop. This fact is due to several aleatory factors that can affect the production line time trend and output, such as strokes, absenteeism, induction of workers, non compliant or damaged raw materials that come to the assembly line. An example of this case can be observed in family C1V, whose trend is steady and increasing through weeks 17 to 19, while in table 3.3 production time $T_{C1V,\,w}$ clearly reduces up to 48% in 3 weeks' time. By giving an example taken from a real working day, if in week 19 the raw material to be assembled on the line is out of tolerance or out of the quality standard or damaged, then the output is going to decrease up to 62% due to

Table 3.5. Production data for the learning curve drawing of family C1B.

Family product C1B	**3**	**4**	**5**	**...**	**13**	**14**	**15**	**16**
$EBQ_{C1B,w}$	20	60	43	...	31	11	23	47
$T_{C1B,w}$	15.3	8.9	7.8	...	10.0	9.5	9.4	7.2
Cumulated qty	20	80	123	...	225	236	259	306

extra non-productive time for problem identifying/solving, selection/waste operations on materials, extra logistics, which have a direct negative impact on workers efficiency, even if their learning ability is actually growing.

Increasing trends that, instead, are placed after an unproductive period, e.g. family code C4V, are explanatory since production break espouse workers to the *forgetting* phenomenon as the assembly starts again. In order to be precise in the learning curves drawing, it has been imagined a continuous flow of production, so production breaks such the one of C4V are being taken into account just for the forgetting phenomenon studying, as explained afterwards. As production lots are greater than 10 units, weeks that show less than 5 units produced have been assimilated to break periods. For every analyzed Project, starting from table 3.4, a new table like 3.5 has been created to draw the suitable learning curve for each family product.

From empirical evidence on the assembly line, time to produce the first unit of each production lot can be stated as follows:

$$T_{1,k} = aT_{std,k} \ with \ a = 5 \div 8 \tag{3.23}$$

where: $\mathrm{T}_{1,\mathrm{k,w}}$ is the actual average production time to assemble the first unit of family k; $\mathrm{T}_{\mathrm{std,k}}$ is the tender evaluated standard time for family k; a is an empirical multiplying factor.

Graph 3.5 shows learning curve obtained from equation 3.23 and table 3.5 and its relative equation for the *j-th* unit is:

$$T_{C1B,j} = 38.366 j^{-0.315} \tag{3.24}$$

where is evident that:

- time to produce the first unit $T_{C1B,W} = 38.366$ manhours;
- learning curve $l = 0.315$, corresponding to 80% learning rate, by meaning that as production doubles, time to produce a new unit decreases of 20% and productivity increases up to 20% correspondingly.

A learning curve as the one reported in graph 3.5 has been created for each family product of the three Projects examined in the following paragraphs.

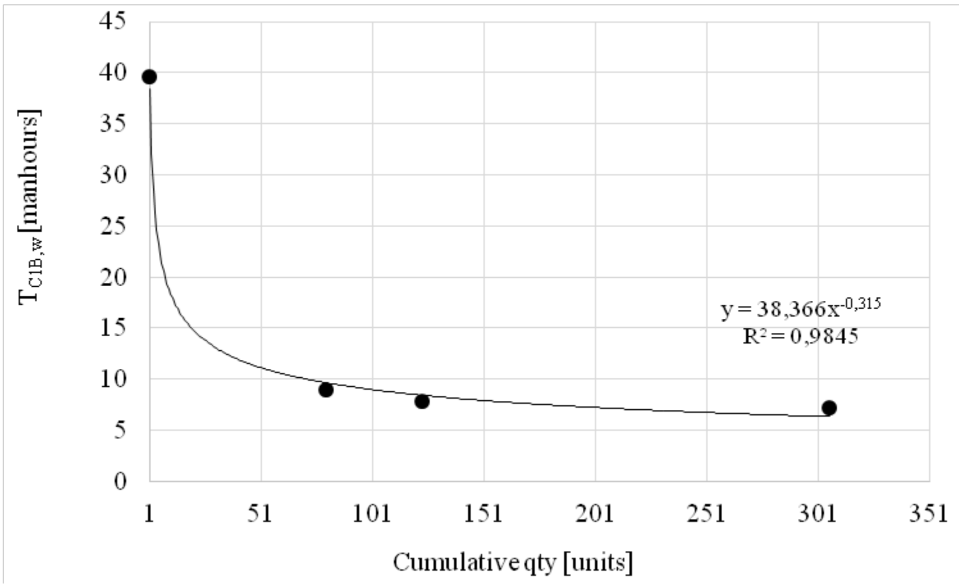


Figure 3.5. Empirical learning curve obtained for family C1B.

The *forgetting* analysis has been conducted following Jaber M.Y. (1996): for each Project there have been isolated family products formed by a significant number of produced units in the considered planning horizon, in order to calculate all of the parameters described in the *learn-forget curve model* when having one or two production runs with one week of forgetting period between them. The goal of this latter study is to verify if production rates after the production break obtained with the manipulation of experimental data (ref. table 3.4), overlap the results that come out from the model calculations, in order to test its reliability and applicability. Experimental data highlighted that duration of the production break that causing total forgetting t_B vary linearly with the degree of assembly difficulty, i.e. *DoD*, as illustrated in figure 3.6.

From experimental data, the linear relationship between $\mathrm{t_B}$ and DoD is expressed by equation 3.25:

$$t_{B,k} = 5DoD_{k,\%} + 5 \tag{3.25}$$

The curve trend shows that time to totally forget grows with the growing of the difficulty in assembling: is evident then, that workers best memorize the assembly sequencing of complex pieces, hence the forgetting phenomenon is impacting less. It is important to underline that the value of $\mathrm{t_B}$ has to be converted into *man-hours* in order to be compliant with SAP data sheets (tables 3.2 and 3.3) with relationship 3.26:

$$t_{B,manhours} = t_{B,weeks}\ d\ h\ p \tag{3.26}$$

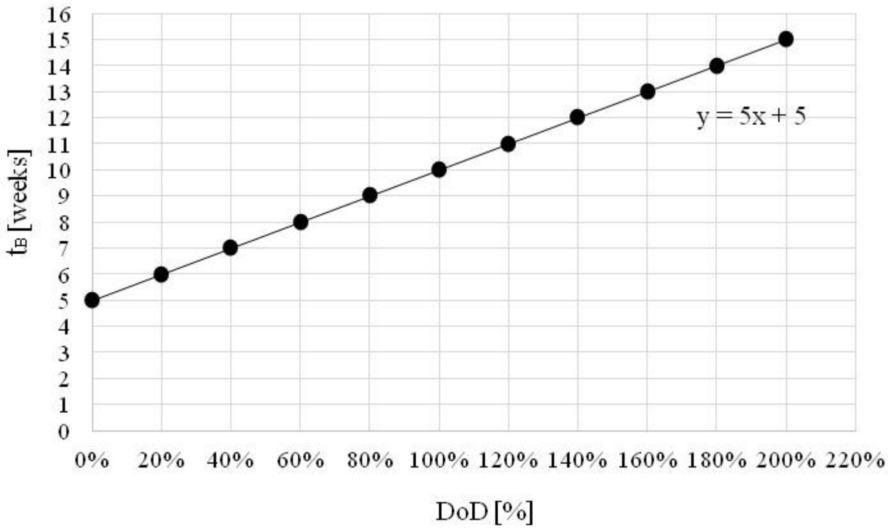


Figure 3.6. Total forgetting time t_B variation according to DoD.

where *d* is the number of working days per weeks, *h* is the number of working hours per day and *p* is the number of workers on the assembly line.

This methodology has been applied to achieve the learning curves of three Permasteelisa Group Curtain Wall Projects, as shown in the following paragraphs.

3.4.2 Tadawul Tower Project

Tadawul Tower Project is a 200 m tall commercial skyscraper based in Riyadh, with 41 floors above ground of curtain wall facade for a total of 40,000 square meters, which has been produced between January 2014 and March 2015 with site completion scheduled within 2016.

The total panels to be assembled for this project were 6982 and they have been split into 14 family products - C1B, C1L, C1V, C2V, C4B, C4L, C4V, C5B, C5L, C5V, C5C, C6L, C6V, C1C - according to the location on the facade and to the different geometry, to which correspond a different assembling sequence and components; each family has a clear identification code, where:

- the first character "C" defines that the product to be produced is a curtain wall panel, which is a *cell* of the facade;
- the second character states the *elevation*, since this tower has an exagonal footprint, this value can vary from 1 to 6;
- the last character recognizes the geometry of the panel itself:

Figure 3.7. The Tadawul Tower, Riyadh.

- V: the panel is *Visual*, by meaning that it is possible to see the external of the building from the internal part since the glass unit is transparent - see figure 3.8 for a better understanding;
- B: the panel is *Blind*, by meaning that it is not possible to see the external of the building from the internal part since behind the glass unit a presswork is installed. Generally these panels are placed on concrete walls or slab - see figure 3.9 for a better understanding;
- C: the panel is a *Corner*, by meaning that it has to be assembled on the junctions between 2 elevations of the building - see figure 3.10 for a better understanding;
- L: the panel is a *Louvre*, by meaning that it has grid elements assembled on it - see figure 3.11 for a better understanding.

Empirical Evidences of The Learning Phenomenon

The learning curves obtained through the implementation of the methodology explained in the previous paragraph on all of the 14 product families are visible in figure 3.13 and the resulting parameters are collected in table 3.6.

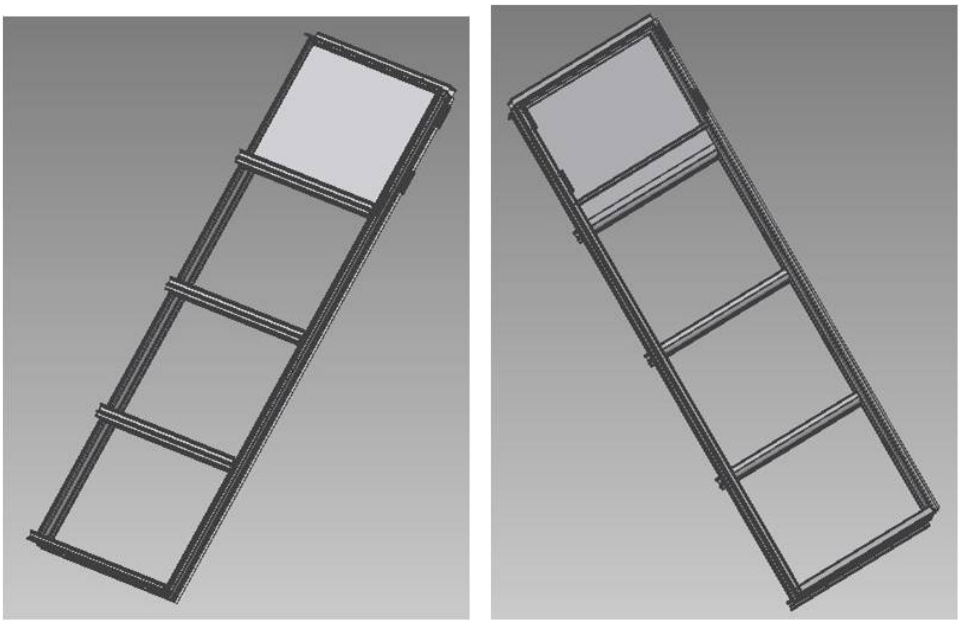


Figure 3.8. Front and back of a C6V panel (courtesy of Permasteelisa Group).

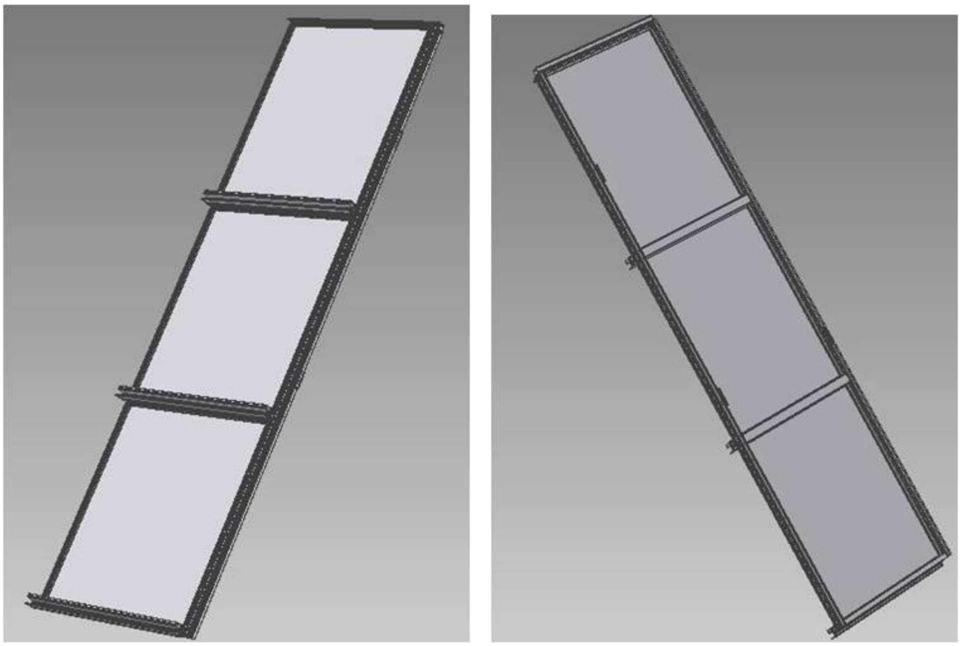


Figure 3.9. Front and back of a C5B panel (courtesy of Permasteelisa Group).

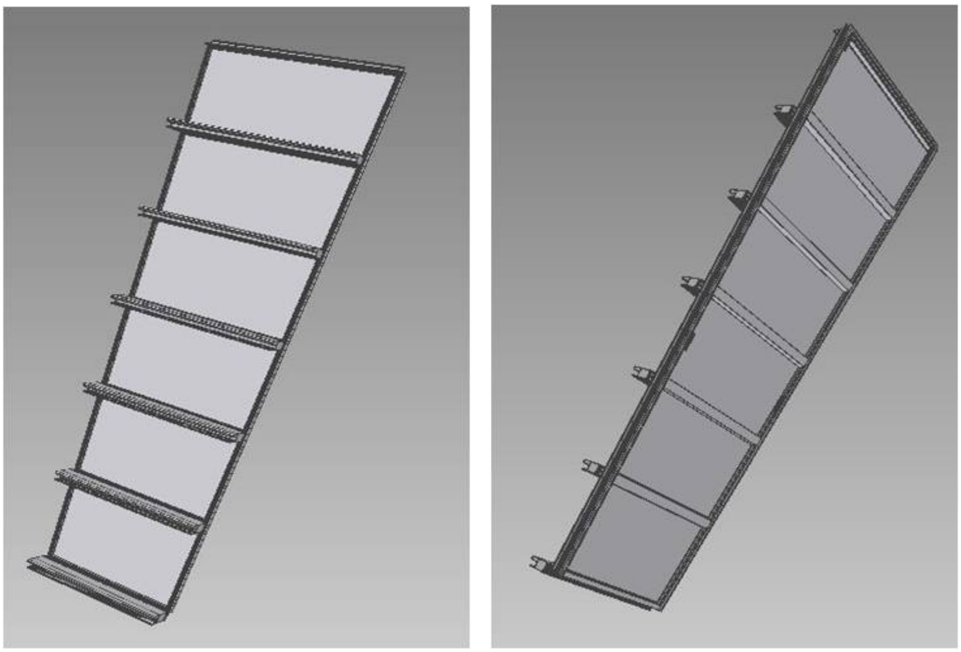


Figure 3.10. Front and back of a C1C panel (courtesy of Permasteelisa Group).

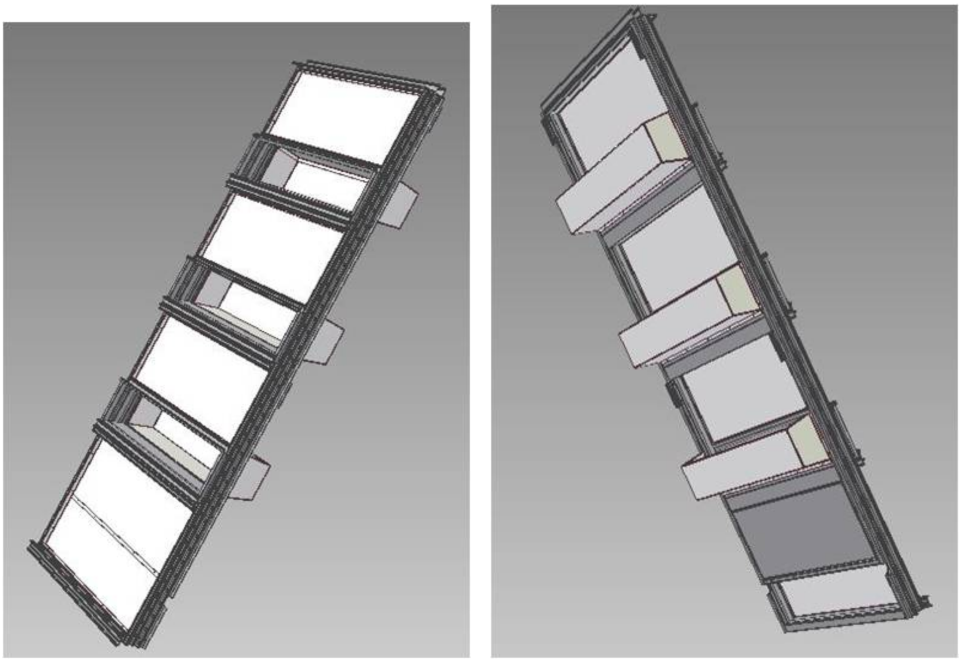


Figure 3.11. Front and back of a C6L panel (courtesy of Permasteelisa Group).

Table 3.6. Learning Curve parameters of Tadawul Tower.

	Experimental data				Learning Curve		
Family	***$DoD_{k,\%}$***	***Produced qty***	***$T_{1,k}$***	**$T_{avg,k}$**	***$T_{1,k}$***	***l***	***$l_{\%}$***
C1B	70	414	39.6	10.2	38.4	0.315	80
C1L	105	148	46.2	10.4	43.4	0.390	76
C1V	0	2811	21.0	4.8	15.8	0.201	87
C2V	0	90	22.8	4.2	22.0	0.432	74
C4B	20	63	30.6	9.0	31.1	0.360	78
C4L	120	57	51.0	9.4	47.3	0.459	73
C4V	0	298	17.5	4.9	17.4	0.273	83
C5B	20	96	30.6	8.1	31.1	0.385	77
C5C	98	102	39.0	11.1	43.5	0.391	76
C5L	120	60	54.0	10.4	53.0	0.452	73
C5V	0	388	21.0	4.0	20.6	0.295	82
C6L	105	62	40.2	8.0	40.4	0.421	75
C6V	0	256	21.0	4.0	19.2	0.322	80
C1C	114	562	48.6	11.1	50.9	0.298	81
					Arithmetic avg	0.357	78
					Weighted avg on qty	0.262	83

This latter shows in the first 5 columns the sympathized production data and in the last 3 columns the parameters of the learning curve, obtained thanks to the experimental data interpolation. It has to be underlined that statistical value of T1 (6th column) are reliable since they are close to the experimental value calculated through equation 3.23 and reported in column 4.

As DoD increases in table 3.6, $T_{1,k}$ and the average production time $T_{avg,k}$ also grow, which is a logical conclusion that the more complexity of the part to be assembled arises, the more time is needed to produce it. Consequently the learning slope follows the same trend too, while the learning rate slows down, by meaning that, the more the piece is complex, the more benefits coming from the learning phenomenon on productivity side are being reached, thus resulting in time efficiency. This evidence is not respected by families C2V, C1B and C1C which are being neglected in this analysis, since a lot of interruptions occurred during their production, so the manifestation of the forgetting phenomenon gives poor significance and reliability to the results. A fundamental evidence of the obtained curves is that as the product to assemble becomes complex, workers learn the assembly sequence in a stronger way, by meaning that they feel more responsibility and conscious of the professional value of what they are doing, of the quality and economic negative impact of their negligence or mistake. By summarizing, there is an increased proactive attitude of operators towards complicated pieces, hence a better memorization of the production process resulting in less vulnerability to *forgetting*. With reference to DoD and learning constant data reported in table 3.6, it is possible to obtain the analytical relationship between the two, shown in figure 3.12, which is instrumental to evaluate from the DoD obtained during the tender preliminary phase, the learning constant to apply to the middle-term production schedule drawing up.

It is suitable to underline that for a DoD up to 2.5 times the base-family, the range of the learning constant is restricted, so it is convenient to use a single value of the learning constant for all of the project family-products

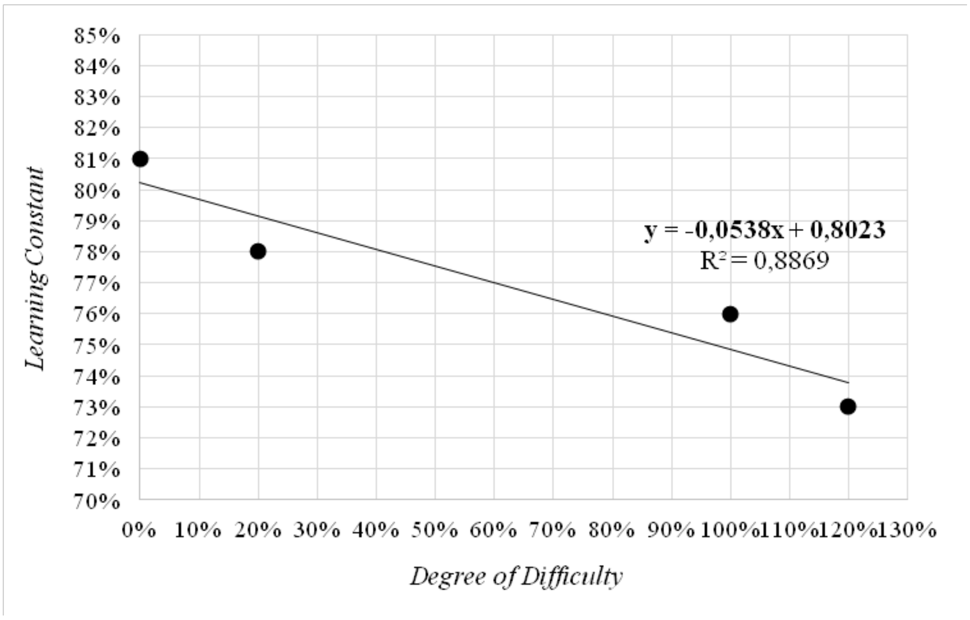


Figure 3.12. Learning constant linear interpolation for Tadawul Tower.

in order to simplify production planning carrying out. This value can be chosen by identifying the *weight average* of the learning constant, made on the basis of quantity-per-family, reported in the bottom of table 3.6. As an alternative, if suitable time and economic resources are available and trade-off between time consumption and result is befitting, then the utilization of an *ad hoc* learning curve for each family, would give out extremely precise pieces of information. The set of all of the learning curves obtained for the project is available in figure 3.13.

The Forgetting Phenomenon Analysis

The forgetting phenomenon is begin studied through Jaber M.Y. (1996), by referring to production data as reported in table 3.5, in order to verify if experimental data are compliant with the time needed for the first production after a break as calculated through the forgetting model.

The analysis concerns family product *C4V*, with learning curve reported in figure 3.14 and the following data:

- first production batch: 12 pcs;
- production break: 1 week with 5 working days and 15 workers on the assembly line, by meaning that $t_b = 600$ manhours;
- learning slope $l = 0.273$;
- time for first piece to be produced $T_1 = 17.38$ manhours;

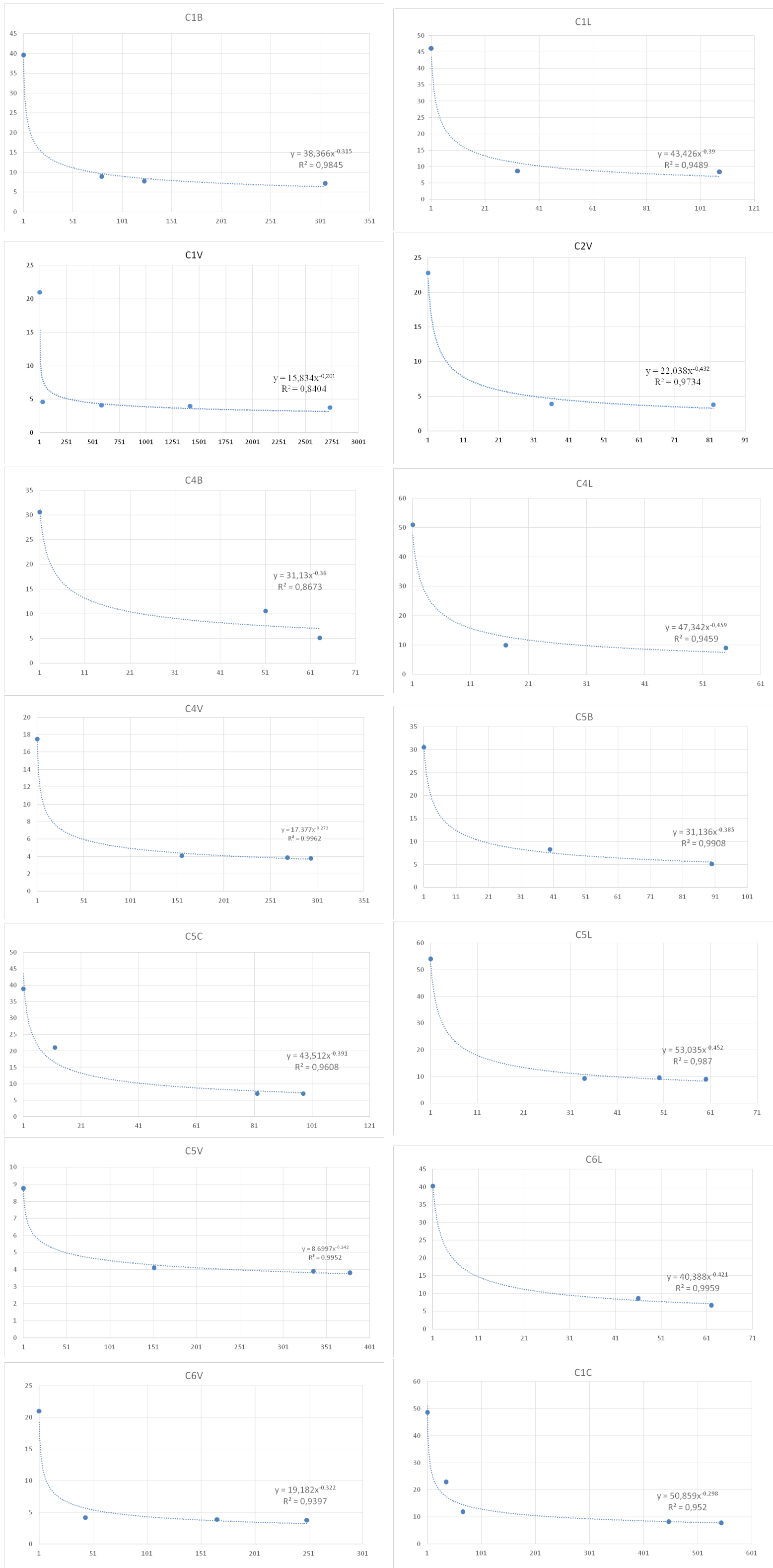


Figure 3.13. Learning curves of Tadawul Tower Project.

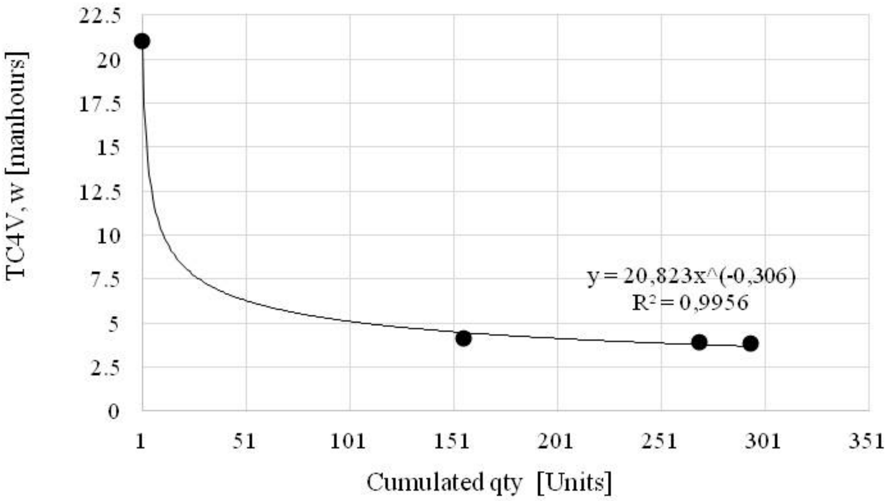


Figure 3.14. Learning curve for Tadawul Tower C4V family product.

- total forgetting time t_B is 5 weeks = 3000 manhours;
- experimental average time to produce the units during the first week after the break $\tilde{T}_{13}$ = 10.6 manhours;
- second production batch: 13 pcs;
- second production break: 600 manhours;
- experimental average time to produce the units during the first week after the second break $\tilde{T}_2$ = 9 manhours;

So by using Jaber M.Y. (1996), the production time to accumulate 12 units, the C ratio and the forgetting slope are easily calculable by applying equations 3.13, 3.16, 3.17 :

$$t(12) = \int_0^q T_1 j^{-l}\, dj = \frac{17.38}{1-0.306} 12^{1-0.306} = 144.90\ manhours$$

$$C = \frac{t_B}{t_{12}} = \frac{3000}{144.90} = 20.70$$

$$f = \frac{l(1-l)\log q}{log(C+1)} = \frac{0.273(1-0.273)\log 12}{\log(20.70+1)} = 0.160$$

This forgetting slope corresponds to a forgetting rate equal to $2^{-0.160}$ = 89.5%. The total amount that would have been accumulated if no interruption occurred is:

$$(q+s) = \left[\frac{1-l}{T_1}t_b + q^{1-l}\right]^{\frac{1}{1-l}} = \left[\frac{1-0.273}{17.38}600 + 12^{1-0.273}\right]^{\frac{1}{1-0.273}} = 113\, units$$

The level of experience expressed in *units* during the first production batch hat is going to be remembered in the second batch is:

$$\alpha_2 = q^{\frac{l+f}{l}}(q+s)^{-\frac{f}{l}} = 12^{\frac{0.273+0.160}{0.273}}(113)^{-\frac{0.680}{0.273}} = 3\ units$$

At this point time to produce the 13-th panel is:

$$\hat{T}_{13} = T_1[\alpha_2 + 1]^{-l} = 17.38[4+1]^{-0.273} = 11.7\ manhours$$

If no interruption occurred, then the time to produce the 13-th unit would have been:

$$T_{13} = T_1[q+1]^{-l} = 17.38[12+1]^{-0.273} = 8.6\ manhours$$

It is evident that the loss of production impacts on the efficiency due to the forgetting phenomenon is 36.0% and that experimental data $\tilde{T}_{13}$ and calculated $\hat{T}_{13}$ value differ of 10.3% in favour of the first one. The second production batch has then 13 units with another 600 manhours production break and the time for the experimental average time to produce the units during the first week of the third lot is 9 manhours. The data of the model for this second batch are the following:

$$t(13+3) = \int_0^q T_1 j^{-l}\, dj = \frac{17.38}{1-0.273}(13+3)^{1-0.273} = 181.1\ manhours$$

$$C = \frac{t_B}{t_{12}} = \frac{3000}{181.1} = 16.56$$

$$f = \frac{l(1-l)\log q}{log(C+1)} = \frac{0.273(1-0.273)\log 13+3}{\log(16.56+1)} = 0.193$$

$$(q+s) = \left[\frac{1-l}{T_1}t_b + q^{1-l}\right]^{\frac{1}{1-l}} = \left[\frac{1-0.273}{17.38}600 + (13+3)^{1-0.273}\right]^{\frac{1}{1-0.273}} = 121\, units$$

$$\alpha_3 = q^{\frac{l+f}{l}}(q+s)^{-\frac{f}{l}} = 12^{\frac{0.273+0.193}{0.273}}(121)^{-\frac{0.193}{0.273}} = 4\ units$$

$$\hat{T}_{26} = \hat{T}_{12+13+1} = T_1[\alpha_3 + 1]^{-l} = 17.38[4+1]^{-0.273} = 11.3\ manhours$$

$$T_{26} = T_{12+13+1} = T_1[q+1]^{-l} = 17.38[12+13+1]^{-0.273} = 7.1\ manhours$$

In this case the loss of efficiency is 59.1%, but in any case the learning process continues even after two interruptions: $\hat{T}_{13} > \hat{T}_{26}$. The difference between the experimental time $\tilde{T}_{26}$ and $\hat{T}_{26}$ is 27.0%. The registered error between experimental data and the calculated one, is due to the fact that it is not possible to know the time to produce the very first unit of the batch, but just a weekly average time is available (see Eq.3.22). It is reasonable to conclude that for the first units of the weekly production, the rate is higher then the average, thus reducing the gap between analysis and real data. In any case the error that would be committed if the forgetting phenomenon would be neglected, more than doubles the one that occurs if considering it, hence the forgetting model is fostered to be used.

3.4.3 Val De Fontenay Project

Val De Fontenay is a 90,000 m^2 office space that has been build to accommodate more than 5,000 employees. Nearly 800 site workers has be working on site at the peak of construction works from 2015 to end of 2016. Paris architect Anne Demians was chosen to lead this project, which will include 5 new buildings, wooded areas, a gym, a business centre and several restaurants.

Figure 3.15. The Val De Fontenay, Paris.

For this project, also, all 7000 panels have been divided into 12 product families - *C1A*, *C1F*, *C1W*, *C2F*,*C3A*, *C3F*,*C4A*, *C4F*, *C5F*,*C5W*,*C6A*,*C6F* - which have specific coding:

- the first character "C" defines the product to be produced is a curtain wall panel, which is a *Cell* of the facade;
- the second character states for a particular *area* of the facade;
- the last character recognizes the geometry of the panel itself:
  - *F*: the panel is *Fixed*, so it is not possible to open the frame, being it blind or visual - see figure 3.16 for a better understanding;
  - *W*: the panel is *Window*, by meaning that the frame is openable - see figure 3.17 for a better understanding;
  - *A*: the panel has a *Angle*, by meaning that it has to be assembled on the junctions between 2 elevations of the building - see figure 3.18 for a better understanding.

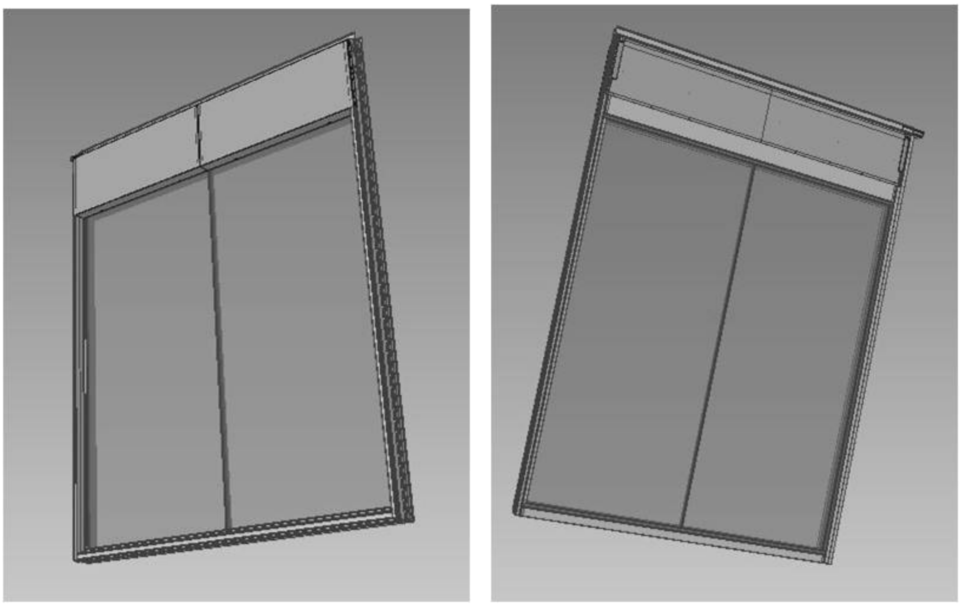


Figure 3.16. Front and back of a C2F panel (courtesy of Permasteelisa Group).

Empirical Evidences of The Learning Phenomenon

The Learning curve analysis has been conducted as explained in paragraph 3.4.1. The learning curves obtained for all of the 12 product families are visible in figure 3.19 and the resulting parameters are collected in table 3.7. This latter shows in the first 5 columns the production data and in the last 3 columns the parameters of the learning curve, obtained thanks to the experimental data interpolation. It has to be underlined that statistical value

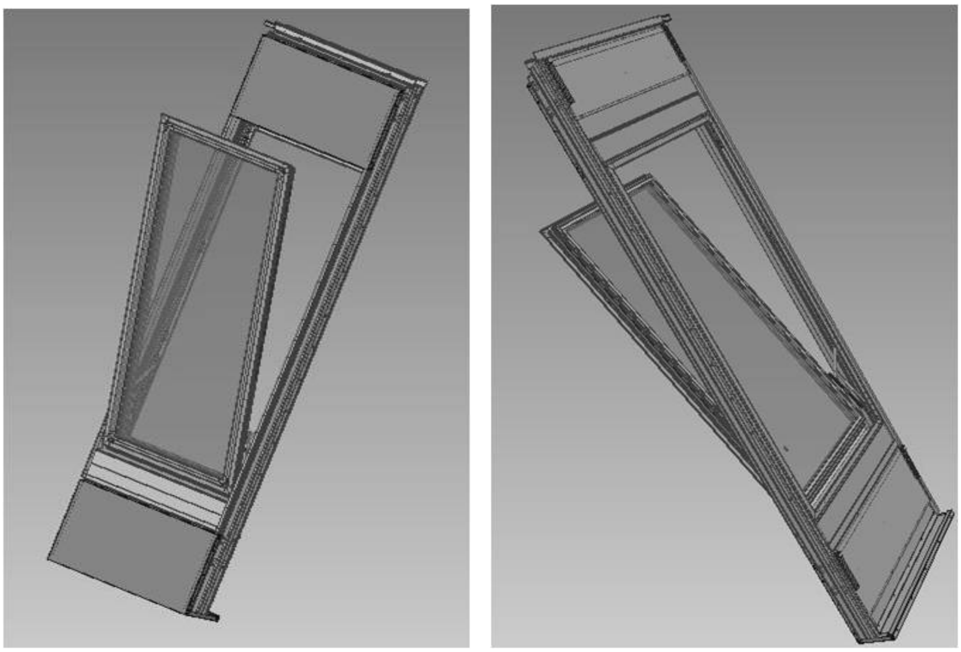


Figure 3.17. Front and back of a C5W panel (courtesy of Permasteelisa Group).

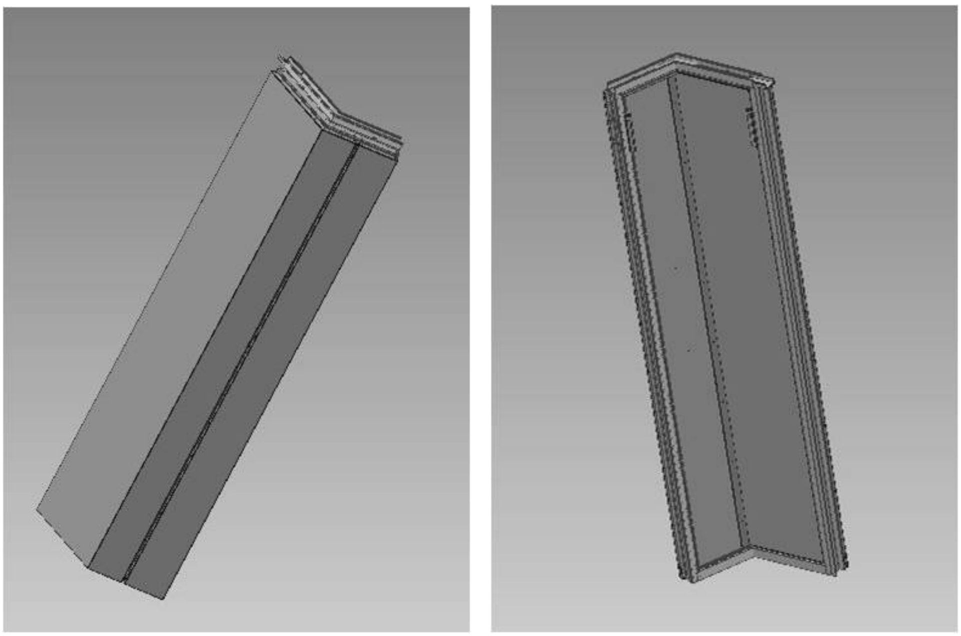


Figure 3.18. Front and back of a C1A panel (courtesy of Permasteelisa Group).

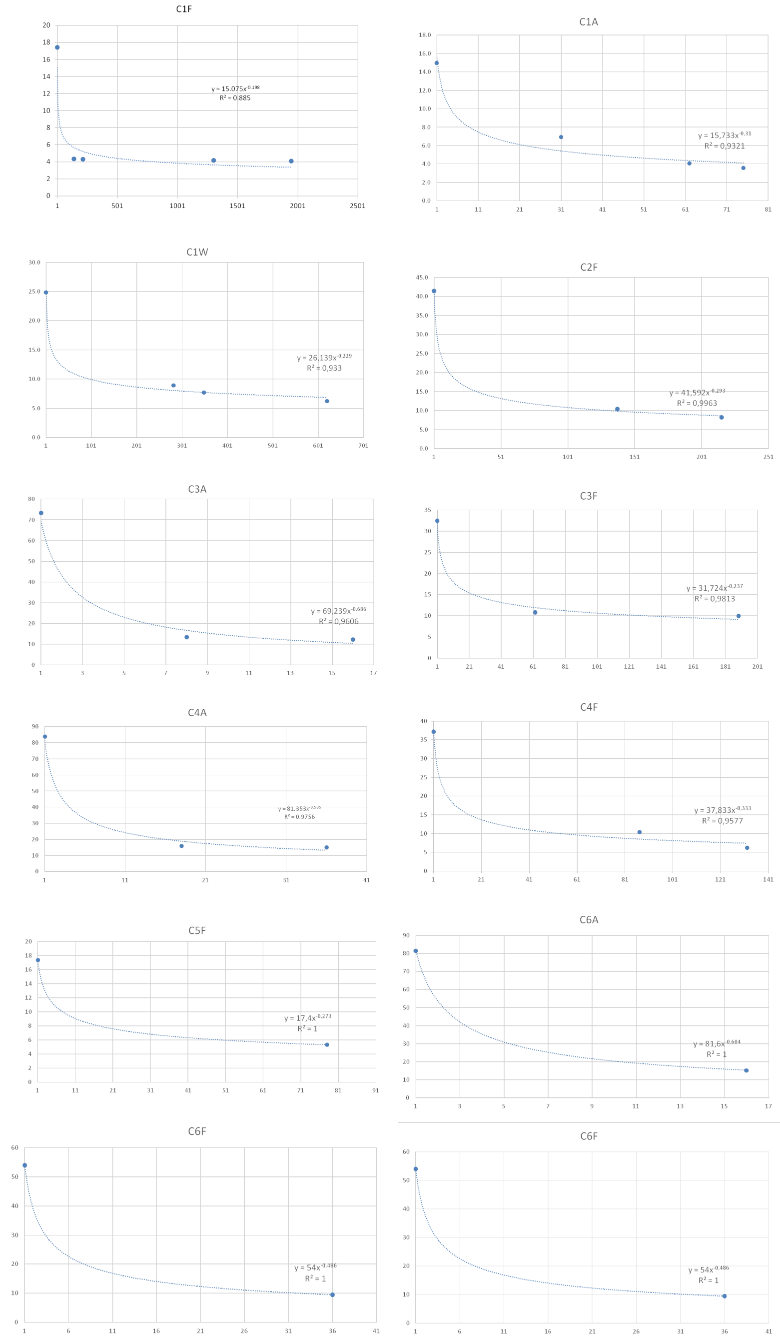


Figure 3.19. Learning curves of Val De Fontenay Project.

Table 3.7. Learning Curve parameters of Val De Fontenay.

	Experimental data				Learning Curve		
Family	$DoD_{k,\%}$	***Produced qty***	$T_{1,k}$	$T_{avg,\ k}$	$T_{1,k}$	l	$l_{\%}$
C1A	0	136	15	5.1	15.7	0.310	81
C1F	0	3338	17.4	5.1	15.1	0.198	87
C1W	53	771	24.9	9.0	26.1	0.229	85
C2F	50	216	41.4	9.3	41.6	0.293	82
C3A	227	16	73.2	15.8	69.2	0.686	62
C3F	86	189	32.4	8.7	31.7	0.237	85
C4A	227	55	84	15.7	81.4	0.505	70
C4F	106	212	37.2	9.6	37.8	0.333	79
C5F	0	78	17.4	4.1	17.4	0.273	83
C5W	31	31	46.2	10.9	46.2	0.921	53
C6A	16	16	81.6	14.7	81.6	0.604	66
C6F	36	36	54	12.0	54.0	0.486	71
					Arithmetic avg	0.423	75
					Weighted avg on qty	0.230	85

of T_1 (6th column) are reliable since they are close to the experimental value calculated through equation 3.23 and reported in column 4.

As it can be noticed, experimental and calculated values of the first unit production time T_1 are nearly overlapping, hence the learning model approximates the real production data very well; as the DoD grows, T_1 and the average production time T_{avg} increase also, by meaning that more complicated units require more time to be produced. As the DoD increases, the learning slope decreases, with the consequent growth of the learning rate, so that the higher the piece is complex, the higher is the benefit obtained by the learning process. Since this trend is not held by families C3F and C5W, as their production has been affected by lots of breaks, which leads to the forgetting phenomenon, their results are being neglected in this analysis. For this project also, there is an evidence that the learning phenomenon impacts the most where the pieces to assemble have more difficulties. This is justified by the fact that when operators deal with complex pieces, they recognize the higher value of the assembled piece, which turns into higher attention, motivation, remembering and less exposures to the forgetting phenomenon. Linear relationship between DoD and learning rate can be appreciated in graph 3.20, where the obtained curve $y = -0.0875x + 0.8553$ can be used to calculate the learning slope that corresponds to a specific tender DoD, in order to take this into account as the production schedule is being written down. By comparing this curve with the Tadawul Project one (image 3.12) the range of the learning curves is wider, so it is suitable to adopt a different learning constant when considering the different product families belonging to the building. These results can be applied to other similar projects so that at the tendering phase it is possible to know in anticipation and in an accurate way the learning phenomenon impact on the production schedule and consequently on the production budget.

The Forgetting Phenomenon Analysis

The forgetting phenomenon is begin studied through Jaber M.Y. (1996) model, by referring to production data as reported in table 3.5, in order to

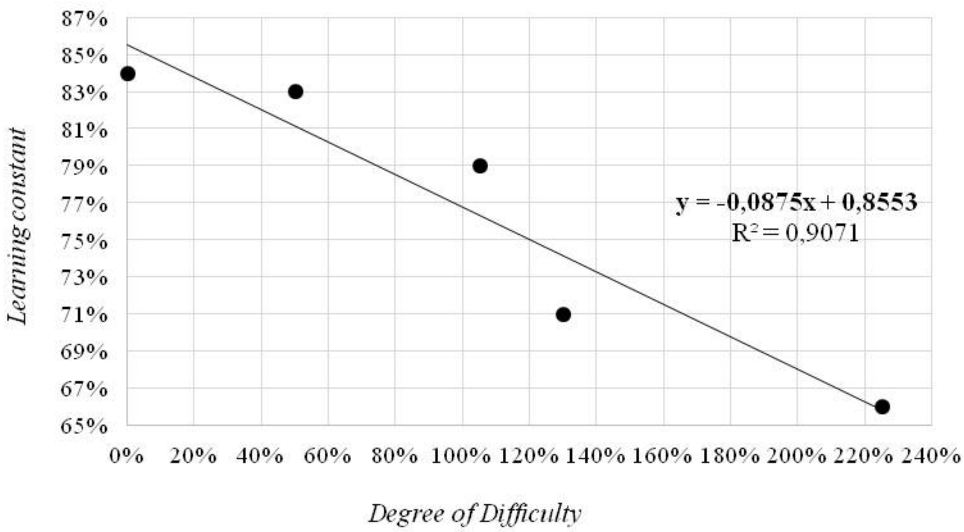


Figure 3.20. Learning constant linear interpolation for Val De Fontenay.

Table 3.8. Forgetting phenomenon on Val De Fontenay C1F.

Run no. i	Qty units	t(q) manhrs	C	f	$f_{\%}$	t_b manhrs	q+s units	α_{i+1} units	$\hat{T}_{1,i}$ manhrs	$T_{1,i}$ manhrs	$\tilde{T}_{1,i}$ manhrs
1	236	1503.7	2.0	0.791	57.8	600	359	44	7.1	5.1	8.1
2	319	2125.4	1.41	1.000	47.8	600	495	69	6.5	4.3	6.9

verify if experimental data are compliant with the time needed for the first production after a break as calculated through the forgetting model. The first analysis concerns family product *C1F*, with learning curve reported in figure 3.21 with $l = 0.198$. The result is shown in table 3.8; time for total forgetting t_B is 4500 manhours.

If the process were not been interrupted, then the percentage of additional effort required to produce the first unit after the first break is 39.2% and 51.2% for the second break; in any case the improvement continues even after the second break, since $\hat{T}_{1,1} > \hat{T}_{1,2}$. The experimental time $\tilde{T}_{1,i}$ for first unit is 14.8% higher for the first break and 6.2% for the second break, if compared to the calculated $\hat{T}_{1,i}$, by meaning that the error when estimating the production time in a tendering phase is smaller (-62.2% for the first run and -87.9% for the second run) when adoping the forgetting model in conjunction with the learning one.

The second product family of this analysis is *C1W*, which has a learning slope $l = 0.229$ (refer to image 3.21). In this case, *C1W* is not a *base* family, but its DoD is 53%, by meaning that the total forgetting time, which can be obtained by the linear relationship shown in graph 3.6, is 7.5 weeks = 4500 manhours. The results are then reported in table 3.9.

If the process were not been interrupted, then the percentage of additional effort required to produce the first unit after the first break is 31.3%

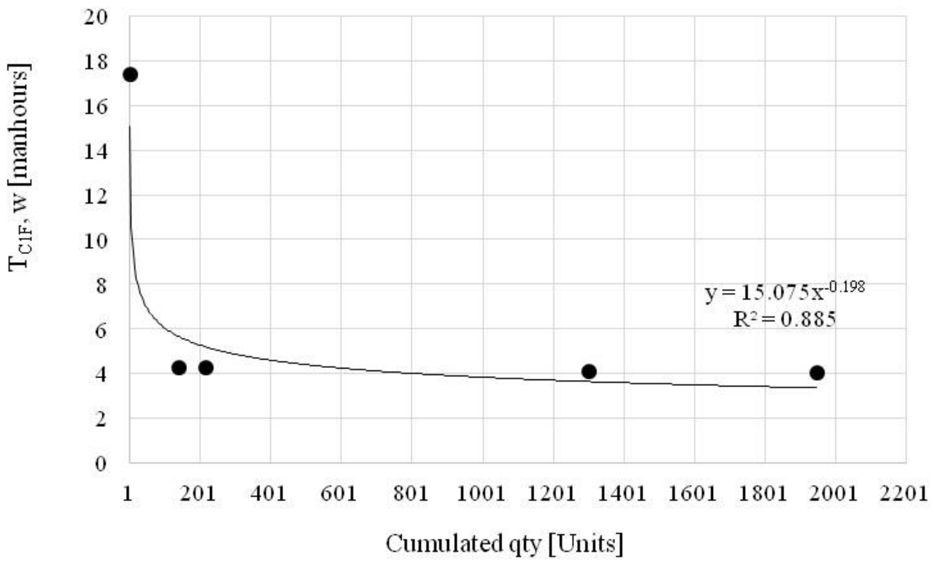


Figure 3.21. Learning curve for Val De Fontenay C1F family product.

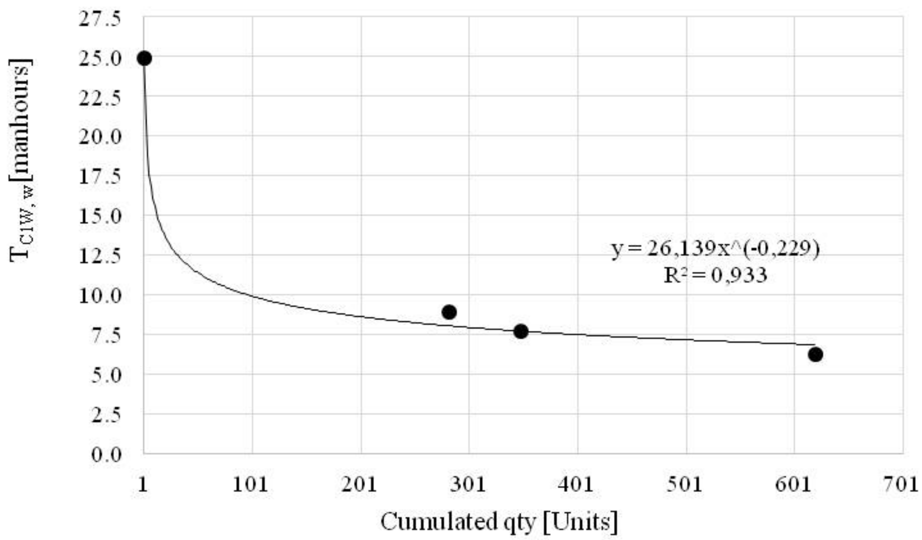


Figure 3.22. Learning curve for Val De Fontenay C1W family product.

Table 3.9. Forgetting phenomenon on Val De Fontenay C1W.

Run no. i	Qty units	t(q) manhrs	C	f	$f_{\%}$	t_b manhrs	q+s units	α_{i+1} units	$\hat{T}_{1,i}$ manhrs	$T_{1,i}$ manhrs	$\tilde{T}_{1,i}$ manhrs
1	78	975.1	4.62	0.446	73.4	600	145.3	23	12.6	9.6	12
2	75	1164.9	3.86	0.512	70.1	600	168.4	29	12	8.3	9.9

Figure 3.23. Manchester One Spinningfields (courtesy of Permasteelisa Group).

and 44.6% for the second break; in any case the improvement continues even after the second break, since $\hat{T}_{1,1} > \hat{T}_{1,2}$. The calculated time $\hat{T}_{1,i}$ time for first unit is 5.0% higher for the first break and 21.2% for the second break, if compared to the calculated $\tilde{T}_{1,i}$, by meaning that the error when estimating the production time in a tendering phase is smaller (-84.0% for the first run and -52.3% for the second run) when adopting the forgetting model in conjunction with the learning one.

3.4.4 Manchester One Spinningfields Project

Manchester One Spinningfields is a 20 level commercial tower, 92 m height, 20000 m^2 located in Manchester, whose production started in February 2016 and is going to end in December 2016, while site activities begun in August 2016 and are going to finish in May 2017.

This research was conducted while the project production was in progress, since not all of the family products have been already produced. For this project, tender product families are slightly different from the lots actually produced, since the slack time between production and site activities start was high and there were not so many differences from one typology to another. Stated this, there have been decided to optimize the production in the best way in order to enhance the margin given by this process, that is why in this paragraph there product families are being replaced by *production lots*. *Production lots* have been then grouping several product families with similar tender production rates and involving 1 or 2 floors each, as

Table 3.10. Production lots of Manchester One Spinningfields.

Production lot	***Description***	***Tender Product Family***	***Bulding Floor***
L01-01A	corner panels	7, 9	1 to 6
L01-02A	flat panels	5, 6, 7	1
L01-02B	flat panels	1, 2, 3	2
L01-02C	flat panels	1, 2, 3	3
L01-03A	flat panels	5, 6, 7	4
L01-03B	flat panels	1, 2, 3	5
L01-03C	flat panels	1, 2, 3	6
L01-03D	flat panels	1, 2, 3	7, 8, 10
L01-04A	corner panels	8, 10, 11	7 to 13

detailed in table 3.10; examples of the geometry of the panels belonging to some production lots are visible in pictures 3.24, 3.25, 3.26.

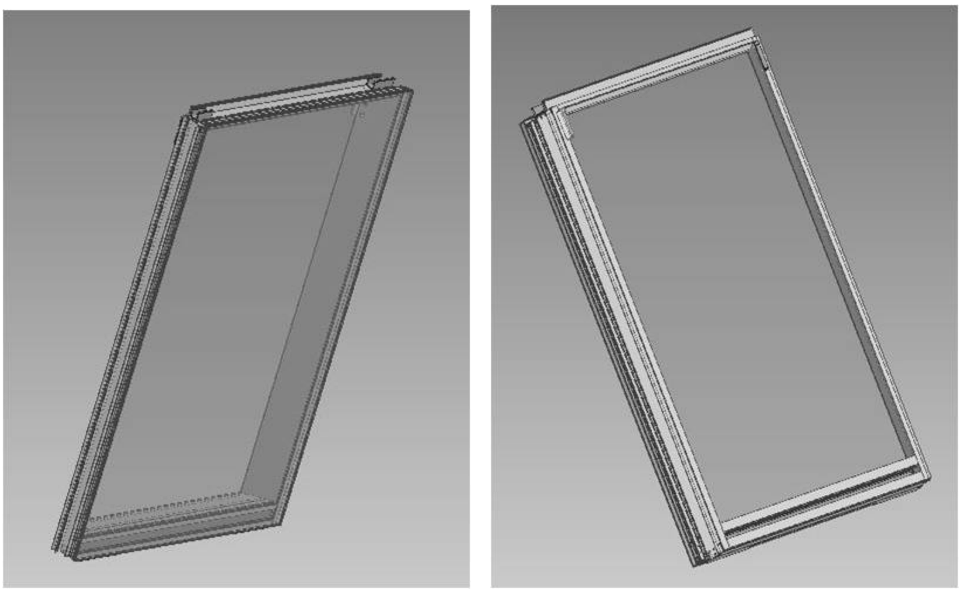


Figure 3.24. Front and back of a L01-01A panel (courtesy of Permasteelisa Group).

Empirical Evidences of The Learning Phenomenon

In table 3.11 the learning curves relevant to each production lot have been reported, by applying methodology proposed in paragraph 3.4.1. For this project also, as DoD increases, time to produce the first unit and average production grow, as a logical consequence.

For the production of this project there have been involved two different assembly lines, C032 and C033, hence one of the goals is to understand if similar lots required similar learning constant even in the case; in table 3.11

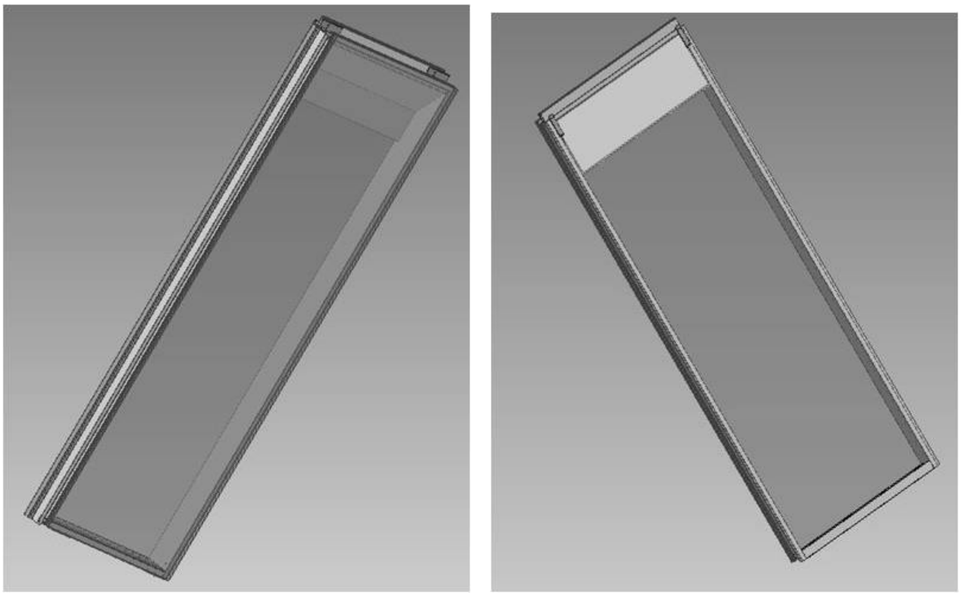


Figure 3.25. Front and back of a L01-02A panel (courtesy of Permasteelisa Group).

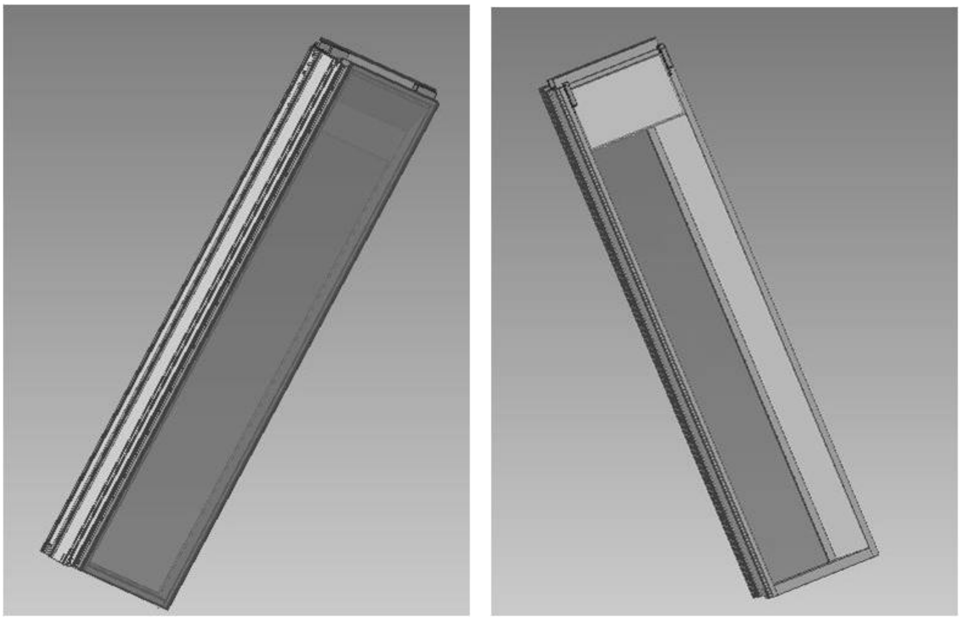


Figure 3.26. Front and back of a L01-03C panel (courtesy of Permasteelisa Group).

Table 3.11. Learning Curve parameters of Manchester One Spinningfields.

	Experimental data				Learning Curve		
Family	$DoD_{k,\%}$	***Produced qty***	***T1,k***	$T_{avg,\ k}$	$T_{1,k}$	l	$l_{\%}$
L01-01A	218	96	80.5	18.8	65.3	0.425	74
L01-02A	28	158	38.4	7.1	35.2	0.384	77
L01-02B	43	138	30.6	5.1	30.6	0.364	78
L01-02C	37	139	37.2	6.2	37.2	0.363	78
L01-03A	98	139	30	5.7	29.8	0.368	77
L01-03B	42	139	21.0	3.5	21.0	0.363	78
L01-03C	37	139	34.8	5.8	34.8	0.364	78
L01-03D	37	143	24.6	5.0	24.6	0.362	78
L01-04A	164	56	46.2	7.8	46.2	0.444	74
					Arithmetic avg	0.382	77
					Weighted avg on qty	0.376	77

Table 3.12. Production macro-lots of Manchester One Spinningfields.

$DoD_{\%}$	Lot	***Assembly line***	***Learning rate***
164-218	L01-01A	C032	74
	L01-04A	C033	74
98	L01-02A	C032	77
	L01-03A	C033	77
42-43	L01-02B	C032	78
	L01-03B	C033	78
37	L01-02C	C032	78
	L01-03C	C033	78
	L01-03D	C033	78

the lots produced by C032 are light grey highlighted, while the ones produced by C033 are in darker grey. As it can be noticed, trends of DoD against learning constant are similar through the lines and that the more the pieces are complex, the more the workers are forgetting phenomenon-proof. For this project it is interesting to see that learning rates have small variations between each other, so that different sublots can be grouped into larger ones, as shown in table 3.12. In this way, it can be ideally imagined to have a single production line producing just 4 macro-lots, which involve lots with similar DoD, by resulting in higher production rates performances because of fully optimization of the assembly line; however this is hardly practicable since it is fundamental to find the correct trade-off between production and site needs.

The relationship between learning constant and DoD is then reported in image 3.27 and it can be used to define the correct learning constant to use according to the foreseen DoD. It is necessary to underline that for this project even if the complexity range is large, the learning constant range is small, so it is suitable to use just a unique value of the learning constant -such as the arithmetic or weighted average- for the whole project to obtain an accurate planning result.

The full set of learning curves drawn for this project are available in figure 3.28.

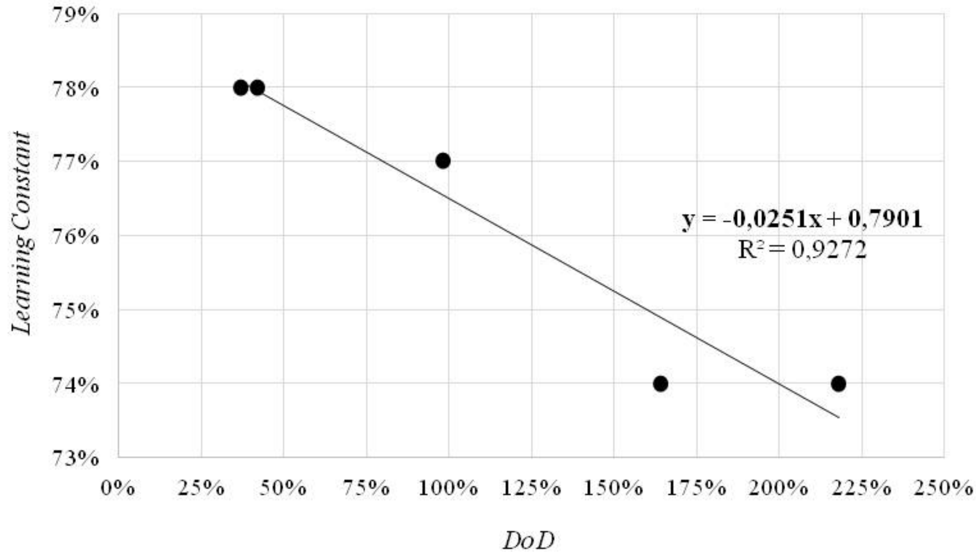


Figure 3.27. Learning constant linear interpolation for Manchester One Spinningfields.

Table 3.13. Forgetting phenomenon on Manchester One Spinningfields L01-02A.

Run no. i	Qty units	t(q) manhrs	C	f	$f_{\%}$	t_b manhrs	q+s units	α_{i+1} units	$\hat{T}_{1,i}$ manhrs	$T_{1,i}$ manhrs	$\tilde{T}_{1,i}$ manhrs
1	137	1182.5	5.7	0.571	63.7	600	266.7	51	7.7	5.3	9

The forgetting Phenomenon Analysis.

The forgetting phenomenon is begin studied through Jaber and Bonney's model, by referring to production data as reported in table 3.5, in order to verify if experimental data are compliant with the time needed for the first production after a break as calculated through the forgetting model. The analysis concerns production lot *L01-02A*, with learning curve reported in figure 3.29 with $l = 0.384$. The result, obtained with the application of Jaber and Bonney, is shown in table 3.13; time for total forgetting t_B is 6000 manhours.

The percentage of additional effort required to produce the first unit after the first break is 45.3% , while the experimental time $\tilde{T}_{1,i}$ time for first unit is 16.8% higher if compared to the calculated $\hat{T}_{1,i}$. Even in this case, the error committed if estimating the production time with the adoption of the forgetting model is the 26.7% smaller, therefore is important for the company to apply this concept in a tendering/budget phase.

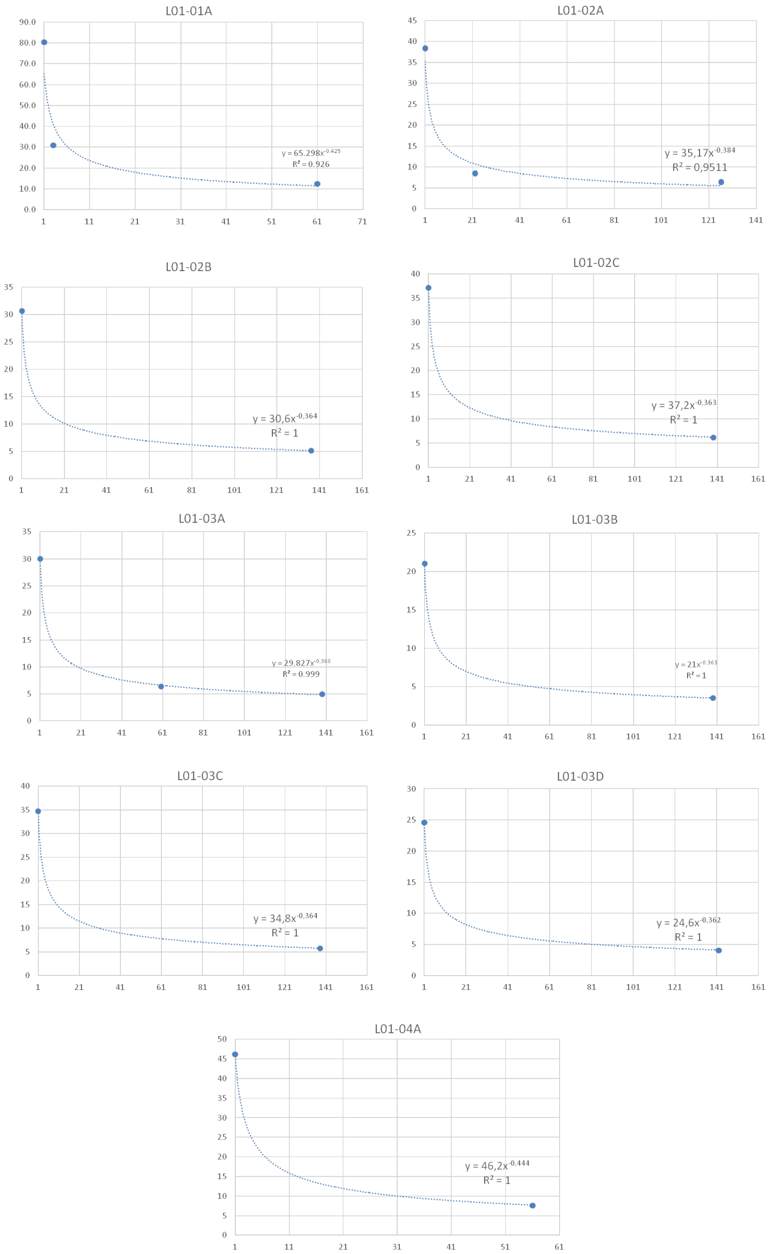


Figure 3.28. Learning curves of Manchester One Spinningfields Project.

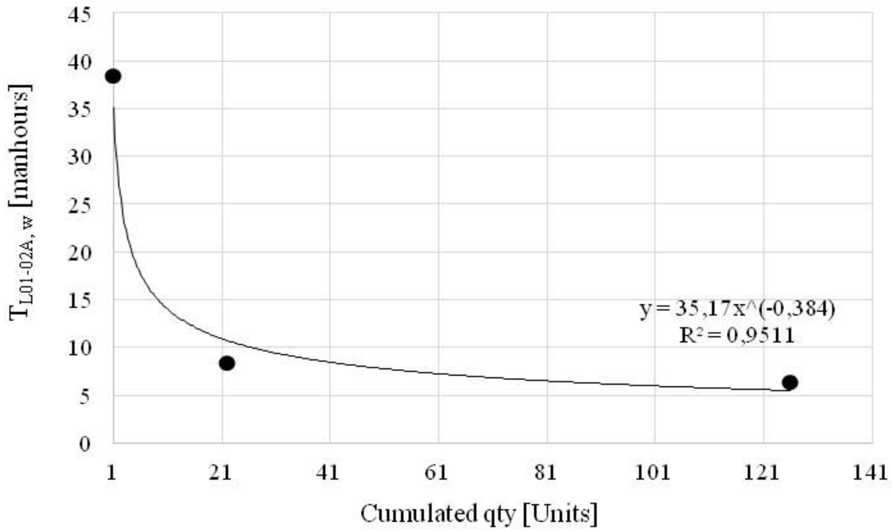


Figure 3.29. Learning curve for Manchester One Spinningfields L01-02A production lot.

3.5 The Learning-Forgetting sequencing

This subsection presents a set of numerical examples that show how the model of Jaber M.Y. (1996) behaves under a variety of forgetting breaks and different values of the learning constant l, obtained from the analysis presented in paragraph 3.4. By studying several production sequences it is possible to understand which is the impact on the schedule evaluation when considering none or an unsuitable learning constant.

Consider a case where the quantity of panels to produce is 600 pcs within 3 horizons, composed by 5 weeks each.The evaluated standard time is 5 hours/panel and the time to produce the first unit being 29 hours. The total capacity of the assembly line per week is considered to be 1500 hours, the total forgetting time is 5 periods (=7500 hours) with a learning constant equal to 0.362. By recapping:

- q_{tot} = 600 pcs;
- Tot weeks = 15;
- Tot horizons = 3;
- t_B = 7500 hours;
- T_{std} = 5 hours;
- T_1 = 29 hours;
- learning constant l = 0.362 (learning rate = 78%).

h type	1					2					5				
Combination	0	0	0	0	1	0	0	0	0	1	0	0	1	0	1
Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Panels/period					100					150			150		200

Figure 3.30. #1 Production sequence.

Figure 3.30 shows the production sequence along the 3 horizons and each sequence has been assigned to a different combination of 0 (meaning no production in the week) and 1 (meaning production on the assembly line during the week), that the mathematical model presented in this thesis in detail in chapter 4 is going to use to assess the production sequence to the suitable learning forgetting features, in accordance to Jaber M.Y. (1996). In fact, each binary combination inside the horizon can be associated to a a finitely production sequence through a suitable parameter (refer to paragraph 4.2.4), which is in turn is used to assign the proper learning and forgetting time intervals.

The production time required to accumulate the first 100 panels, the C ratio value, in accordance to Eq. 3.13, are:

$$t(100) = \int_0^q T_1 j^{-l}\, dj = \frac{29}{1-0.362} 100^{1-0.362} = 870\ manhours$$

$$C = \frac{t_B}{t_{100}} = \frac{7500}{870} = 8.62$$

Forgetting slope for the second production cycle can be calculated as follows:

$$f = \frac{l(1-l)\log q}{log(C+1)} = \frac{0.362(1-0.362)\log 100}{\log(8.62+1)} = 0.47$$

This forgetting slope corresponds to a forgetting rate equal to $2^{-0.47} = 72\%$. The total amount that would have been accumulated if no interruption occured and a 4 break period is:

$$(q{+}s) = \left[\frac{1-l}{T_1} t_b + q^{1-l}\right]^{\frac{1}{1-l}} = \left[\frac{1-0.362}{29} 6000 + 100^{1-0.362}\right]^{\frac{1}{1-0.362}} = 2551\ units$$

The level of experience expressed in *units* during the first production batch hat is going to be remembered in the second batch is:

$$\alpha_2 = q^{\frac{l+f}{l}} (q{+}s)^{-\frac{f}{l}} = 100^{\frac{0.362+0.47}{0.362}} (2551)^{-\frac{0.47}{0.362}} = 1\ unit$$

At this point time to produce the 101-st panel is:

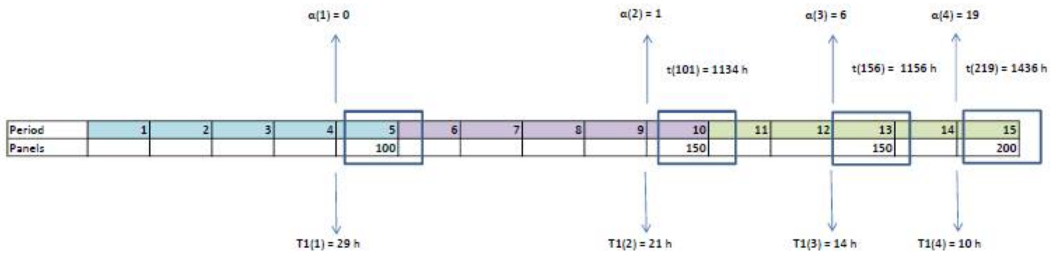


Figure 3.31. #1 Production sequence with forgetting model results.

$$\hat{T}_{101} = T_1[\alpha_2 + 1]^{-l} = 29[1 + 1]^{-0.362} = 21 \; manhours$$

If no interruption occurred, then the time to produce the same unit would have been:

$$T_{101} = T_1[q + 1]^{-l} = 29[100 + 1]^{-0.362} = 6 \; manhours$$

The calculations by extending the same procedure to the production batches of periods 10, 13 and 15 are shown in the first part of table 3.15. In figure 3.31 the results of the application of Jaber M.Y. (1996) on the same example have been visually represented on the planning horizon for a better understanding of all of the interactive steps, which are the followings:

- period 5 is the very first production period, so the units remembered from the past production are α_1=0; time to produce the first panel equals the forecast tender evaluation, which is $T_{1,1}$ = 29 hours;
- second production batch benefits of α_2=1 remembered unit from period 5, disempowered by the 4 periods break; time to produce the first panel improved to $T_{1,2}$ = 21 hours (-27.6%); time to produce the 101 units is t(101)=1134 hours;
- at the beginning of 13th period the accumulated level of experience is α_3=6; time for first unit improves again to $T_{1,3}$=14 hour (-33%)s; time to produce the 156 units is t(156)=1156 hours;
- at the end of the horizon, remembered units are α_4=19; time to produce the first unit after the break is 10 hours (-28.5%); time to produce the 219 pcs is t(219)=1436 hours.

Equivalent logic has been used for a total of 16 different sequences and 4 different learning constants; the data input for each production system considered, being them spread over 15 periods grouped into 3 horizon, all are visible in table 3.14. All of the calculation made for the sequences belonging

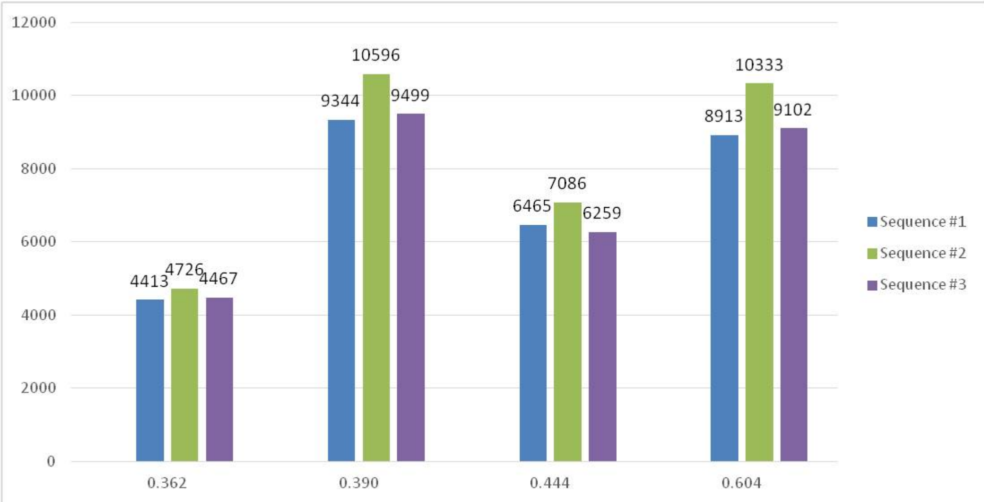


Figure 3.32. Total production time behaviour with different learning constants [manhours].

to the 4 different considered production systems are shown in tables 3.15-3.22 and each sequence is visually available in figure 3.33. In this latest picture, total times to produce the production batches are reported for each period and the very last column on the right represents the additional percentage of production time respect to the one calculated without the learning-forgetting model application. It is evident that this percentage is highly influenced by the production sequence: for example by taking into account $l = 0.362$, the additional time respect to the standard required to complete the batches within the 3 horizon, may vary between 19% (sequence #15), when there is a leveled production and just one break shorter than the total forgetting time t_B, and 61% (sequence #2), when there is a total of 4 breaks, at the end of every production period. Significant deviations can be seen also if taking into account the same production sequence while varying the learning constant: in sequence #5 production time can increase from 4678 manhours ($l = 0.362$) to 9820 manhours ($l = 0.390$), which is approximately 110% more.

Different impact of the learning constant on production time calculation is also clear when comparing the three sequences in picture 3.32, while by having a glance at histograms grouped by learning constant, it comes to the surface which is the impact of the kind of sequence. In the cases of $l=0.390$ and $l=0.604$, the relevance of the way the production in sequenced is greater, being it approximately 13.4% and 15.9% namely when comparing the first and the second sequences.

By having a general overview, as better focused in picture 3.34, it is noticeable that the total production time calculated through Jaber M.Y. (1996) is always higher than the one simply evaluated as the multiplying of the

# Sequence	Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Total time	Additional production time
1	H type			1					2					5				
	Lot qty	0	0	0	0	100	0	0	0	0	150	0	0	150	0	200		
	Time l = 0.362					870					1123			1111		1309	4413	50%
	Time l = 0.390					1877					2394			2352		2721	9344	35%
	Time l = 0.444					1327					1655			1628		1856	6465	13%
	Time l = 0.604					1973					2301			2241		2400	8913	53%
2	H type			1					4					2				
	Lot qty	0	0	150	0	0	100	0	100	0	100	0	150	0	0	0		
	Time l = 0.362			1127			851		830		828		1089.458				4726	61%
	Time l = 0.390			2404			1818		1748		1737		2277.561				9985	45%
	Time l = 0.444			1662			1286		1238		1232		1425.757				6844	20%
	Time l = 0.604			2316			1879		1764		1748		2129.485				9837	69%
3	H type			3					2					1				
	Lot qty	160	0	0	0	160	0	0	160	0	0	0	60	60	0	0		
	Time l = 0.362	1174				1167			1157.492				968.6889				4467	52%
	Time l = 0.390	2501				2478			2447.35				2072.821				9499	38%
	Time l = 0.444	1723				1708			1687.554				1140.827				6259	10%
	Time l = 0.604	2376				2344			2300.041				2081.588				9102	56%
4	H type			3					0					3				
	Lot qty	0	0	125	0	100	0	0	0	0	0	150	0	75	75	75		
	Time l = 0.362			1003		825						1124.16		1418			4370	49%
	Time l = 0.390			2151		1733						2397.781		2945			9226	34%
	Time l = 0.444			1502		951						1425.841		2138			6017	6%
	Time l = 0.604			2155		1742						2306.795		2542			8745	50%
5	H type			1					3					6				
	Lot qty	35	35	30	10	0	55	55	40	0	70	70	0	110	0	90		
	Time l = 0.362	925					1090.693				1027			871		766	4678	59%
	Time l = 0.390	1990					2287.965				2135			1809		1598	9820	42%
	Time l = 0.444	1046					1566.134				1485			1278		1142	6516	14%
	Time l = 0.604	2048					2143.274				2008			1776		1632	9607	65%
6	H type			3					5					2				
	Lot qty	0	200	0	0	60	0	40	0	0	90	60	30	90	30	0		
	Time l = 0.362		1354			602		449.3541			1747						4152	41%
	Time l = 0.390		2865			1291		957.3353			3648						8762	27%
	Time l = 0.444		1901			938		711.5651			2851						6401	12%
	Time l = 0.604		2596			1468		1140.976			3019						8224	41%
7	H type			0					1					3				
	Lot qty	0	0	0	0	0	130	80	0	0	0	90	0	0	170	130		
	Time l = 0.362						1396.698					803			1744		3944	34%
	Time l = 0.390						2951.706					1728			3640		8319	21%
	Time l = 0.444						2004.26					1229			2851		6084	7%
	Time l = 0.604						2646.176					1842			3009		7498	29%
8	H type			1					5					2				
	Lot qty	0	0	0	100	50	50	0	150	35	50	0	120	45	0	0		
	Time l = 0.362				1354				1447.907				1124.587				3926	34%
	Time l = 0.390				2865				2993.485				2257.574				8116	18%
	Time l = 0.444				2000				2115				1650				5765	1%
	Time l = 0.604				2596				2551.257				2059.816				7207	24%
9	H type			3					2					3				
	Lot qty	100	120	0	0	130	50	0	0	0	0	0	100	50	0	50		
	Time l = 0.362	1439				1246							1124.16			498	4307	47%
	Time l = 0.390	3037				2617							2397.781			1039	9090	32%
	Time l = 0.444	2091				1800							1657.393			764	6312	11%
	Time l = 0.604	2695				2405							2306.795			1158	8565	47%
10	H type			1					2					3				
	Lot qty	0	0	50	40	90	0	0	120	80	0	110	0	110	0	0		
	Time l = 0.362			1266					1337.349			858		878			4339	48%
	Time l = 0.390			2687					2812.752			1773		1828			9101	32%
	Time l = 0.444			1840					1900.817			1254		1293			6287	10%
	Time l = 0.604			2489					2524.741			1733		1804			8551	47%
11	H type			1					5					3				
	Lot qty	0	0	0	50	80	100	0	145	0	0	0	150	0	35	40		
	Time l = 0.362		1480.161						1034.785				1118.745		667		4301	46%
	Time l = 0.390		3120.134						2119.625				2379.512		1394		9013	31%
	Time l = 0.444		2185.85						1491.904				1645.694		1003		6327	11%
	Time l = 0.604		2743.242						1985.472				2281.13		1461		8471	46%
12	H type			3					5					5				
	Lot qty	100	70	0	40	40	25	0	0	0	25	45	55	0	0	200		
	Time l = 0.362	1221			840						995					1341	4397	50%
	Time l = 0.390	2595			1752						2128					2823	9298	35%
	Time l = 0.444	1782			1238						1486					1901	6407	12%
	Time l = 0.604	2434			1732						2120					2537	8823	52%
13	H type			1					1					3				
	Lot qty	120	0	0	0	0	80	80	80	0	0	0	130	0	110	0		
	Time l = 0.362	977					1517.386						1018.75		878		4392	49%
	Time l = 0.390	2098					3193.356						2161.089		1838		9291	35%
	Time l = 0.444	1468					2280.845						1517.443		1297		6564	15%
	Time l = 0.604	2120					2777.928						2143.284		1816		8858	52%
14	H type			1					3					1				
	Lot qty	0	0	0	100	0	150	0	75	75	0	0	50	50	100	0		
	Time l = 0.362				870		1093.414		1076.588				1337.933				4378	49%
	Time l = 0.390				1877		2296.803		2238.671				2812.738				9225	34%
	Time l = 0.444				1327		1589.519		1425.729				1912.488				6255	10%
	Time l = 0.604				1973		2154.981		2079.437				2524.902				8732	50%
15	H type			1					2					2				
	Lot qty	60	60	60	60	60	0	0	0	60	60	60	60	60	0	0		
	Time l = 0.362	1754								1745.557							3499	19%
	Time l = 0.390	3669								3619.192							7288	6%
	Time l = 0.444	2851								2850.838							5702	0%
	Time l = 0.604	3048								3005.274							6053	4%
16	H type			3					3					1				
	Lot qty	200	0	0	110	0	20	50	0	40	0	0	0	80	100	0		
	Time l = 0.362	1354			903.0008		645.9603			443.0167				1261			4607	57%
	Time l = 0.390	2865			1920		1357			933				2673			9749	41%
	Time l = 0.444	1901			1350		980			696				1711			6638	16%
	Time l = 0.604	2596			1944		1452			1099				2469			9558	64%

Figure 3.33. Production time comparisons between 16 production sequences according to different learning constants.

Table 3.14. Data input for the analysis of the learning-forgetting phenomenon on different production systems.

	1	**2**	**3**	**4**
Qty to produce	600	600	600	600
Total forgetting time t_B [manhours]	7500	7500	7500	7500
Evaluated standard production time per unit t_{std} [manhours]	4.9	11.5	9.5	9.7
Production time for first unit T_1[manhours]	29	69	57	126
learning constant l	0.362	0.390	0.444	0.604

tender standard time by the quantity to produce. The lack of consideration of the learning-forgetting phenomenon in the production planning misleading since the production time is under-estimated up to 69%, with negative consequences on the actual planning in terms of time and capacity on the assembly line, causing delays on the general Project Plan. This misalignment increases with the number of stops on the assembly line since the benefits that comes from the learning effect exploiting is limited by the forgetting phase and, as per graph in figure 3.35 a potential expression explicates this relationship.

The importance of the choice of the correct learning constant is highlighted by histograms in figure 3.36, where the production system considered is the 3rd of table, whose standard production time for a batch of 600 units is 600pcs $\cdot$ 9.5hrs = 5700 hrs and whose correct learning constant is l= 0.444. This total standard time is represented by a red-dot line, while histograms represent the total production time for different sequences (#1, #8, #15) along the various learning constant. If the chosen learning constant would have been l = 0.390, then the danger for the firm is to under-evaluate the total production time in all of the three sequences up to 42% (sequence #15) respect to the total standard time; on the contrary, if the used learning constant would have been l= 0.362 or l= 0.604, then the total production time would have been over-estimated up to 63.9% (sequence #1). In both of the cases, the choice of the wrong learning constant could mislead to squeezed or extended time and resource plannings.

Table 3.15. Learning-Forgetting phenomenon on different production sequences.

(a) Sequence #1

l	Run no. i	q units	t(q) manhrs	C	f	$f_{\%}$	t_b manhrs	q+s units	$q_i+\alpha_{i+1}$ units	$\hat{T}_{1,i}$ manhrs	$T_{1,i}$ manhrs	$T_{avg,i}$ manhrs
0.362	1	100	870	8.62	0.00	100	6000	2551	0	29	29	9
	2	150	1134	6.61	0.47	72	3000	1150	1	6	21	7
	3	150	1156	6.49	0.57	67	1500	575	6	4	14	7
	4	200	1436	5.22	0.58	67	-	-	19	3	10	7
0.390	1	100	1877	4.00	0.00	100	6000	1050	0	69	69	19
	2	150	2420	3.10	0.68	62	3000	569	2	11	47	16
	3	150	2487	3.02	0.85	56	1500	344	9	8	29	16
	4	200	3107	2.41	0.87	55	-	-	28	7	18	14
0.444	1	100	1327	13.19	0.00	100	6000	2161	0	57	57	13
	2	150	1671	10.47	0.43	74	3000	962	2	7	37	11
	3	150	1694	10.33	0.51	70	1500	489	7	5	22	11
	4	200	2031	8.62	0.51	70	-	-	24	4	14	9
0.604	1	100	1973	3.80	0.00	100	6000	3402	0	126	126	20
	2	150	2326	3.22	0.70	61	3000	1229	2	8	70	15
	3	150	2367	3.17	0.83	56	1500	547	8	4	32	15
	4	200	2733	2.74	0.85	56	-	-	28	3	17	12

(b) Sequence #2

l	Run no. i	q units	t(q) manhrs	C	f	$f_{\%}$	t_b manhrs	q+s units	$q_i+\alpha_{i+1}$ units	$\hat{T}_{1,i}$ manhrs	$T_{1,i}$ manhrs	$T_{avg,i}$ manhrs
0.362	1	150	1127	6.66	0.00	100	3000	1147	0	29	29	8
	2	100	904	8.30	0.57	67	1500	492	6	5	14	9
	3	100	944	7.94	0.48	72	1500	505	14	4	11	8
	4	100	949	7.90	0.50	71	1500	506	15	4	11	8
	5	150	1196	6.27	0.50	71	-	-	15	3	11	7
0.390	1	150	2404	3.12	0.00	100	3000	566	0	69	69	16
	2	100	1973	3.80	0.84	56	1500	274	9	10	29	18
	3	100	2099	3.57	0.71	61	1500	291	20	8	21	17
	4	100	2119	3.54	0.75	59	1500	293	22	7	20	17
	5	150	2616	2.87	0.76	59	-	-	22	6	20	15
0.444	1	150	1662	4.51	0.00	100	3000	959	0	57	57	11
	2	100	1380	5.44	0.72	61	1500	403	7	6	22	13
	3	100	1447	5.18	0.62	65	1500	420	17	5	16	12
	4	100	1456	5.15	0.65	64	1500	422	18	4	15	12
	5	150	1601	4.69	0.65	64	-	-	18	4	15	10
0.604	1	150	2316	3.24	0.00	100	3000	1223	0	126	126	15
	2	100	2037	3.68	0.83	56	1500	437	8	6	33	19
	3	100	2122	3.53	0.73	60	1500	464	20	4	20	18
	4	100	2135	3.51	0.76	59	1500	468	22	4	19	17
	5	150	2447	3.06	0.76	59	-	-	22	3	19	14

Table 3.16. Learning-Forgetting phenomenon on different production sequences.

(a) Sequence #3

l	Run no. i	q units	t(q) manhrs	C	f	$f_{\%}$	t_b manhrs	q+s units	$q_i+\alpha_{i+1}$ units	$\hat{T}_{1,i}$ manhrs	$T_{1,i}$ manhrs	$T_{avg,i}$ manhrs
0.362	1	160	1174	6.39	0.00	100	4500	1890	0	29	29	7
	2	160	1188	6.31	0.59	67	3000	1174	3	5	18	7
	3	160	1204	6.23	0.59	66	4500	1906	6	4	14	7
	4	120	993	7.55	0.60	66	-	-	3	3	18	8
0.390	1	160	2501	3.00	0.00	100	4500	865	0	69	69	16
	2	160	2536	2.96	0.87	55	3000	589	4	10	38	15
	3	160	2586	2.90	0.88	54	4500	882	9	7	28	15
	4	120	2138	3.51	0.90	54	-	-	4	6	37	17
0.444	1	160	1723	4.35	0.00	100	4500	1611	0	57	57	11
	2	160	1743	4.30	0.75	60	3000	989	3	6	30	11
	3	160	1768	4.24	0.75	59	4500	1633	8	4	22	11
	4	120	1173	6.40	0.76	59	-	-	3	4	30	10
0.604	1	160	2376	3.16	0.00	100	4500	2341	0	126	126	15
	2	160	2397	3.13	0.85	55	3000	1270	4	6	50	15
	3	160	2427	3.09	0.86	55	4500	2386	9	4	32	14
	4	120	2147	3.50	0.87	55	-	-	4	3	49	17

(b) Sequence #4

l	Run no. i	q units	t(q) manhrs	C	f	$f_{\%}$	t_b manhrs	q+s units	$q_i+\alpha_{i+1}$ units	$\hat{T}_{1,i}$ manhrs	$T_{1,i}$ manhrs	$T_{avg,i}$ manhrs
0.362	1	125	1003	7.48	0.00	100	1500	524	0	29	29	8
	2	100	956	7.85	0.52	70	7500	3532	16	5	11	8
	3	150	1132	6.63	0.50	71	1500	567	1	4	23	7
	4	225	1536	4.88	0.57	67	-	-	19	3	10	6
0.390	1	125	2151	3.49	0.00	100	1500	298	0	69	69	17
	2	100	2128	3.52	0.77	59	7500	1459	23	10	20	17
	3	150	2414	3.11	0.76	59	1500	333	1	8	53	16
	4	225	3300	2.27	0.84	56	-	-	27	7	19	13
0.444	1	125	1502	4.99	0.00	100	1500	434	0	57	57	12
	2	100	1134	6.61	0.67	63	7500	3106	19	7	15	10
	3	150	1442	5.20	0.58	67	1500	480	2	5	37	10
	4	225	2386	3.14	0.68	62	-	-	26	4	13	10
0.604	1	125	2155	3.48	0.00	100	1500	475	0	126	126	17
	2	100	2140	3.51	0.77	59	7500	5496	23	7	19	17
	3	150	2322	3.23	0.76	76	1500	531	1	5	83	15
	4	225	2843	2.64	0.83	83	-	-	27	4	17	11

Table 3.17. Learning-Forgetting phenomenon on different production sequences.

(a) Sequence #5

l	Run no. i	q units	t(q) manhrs	C	f	$f_{\%}$	t_b manhrs	q+s units	$q_i+\alpha_{i+1}$ units	$\hat{T}_{1,i}$ manhrs	$T_{1,i}$ manhrs	$T_{avg,i}$ manhrs
0.362	1	110	925	8.11	0.00	100	1500	498	0	29	29	8
	2	150	1194	6.28	0.49	71	1500	588	14	5	11	7
	3	140	1176	6.38	0.59	66	1500	582	20	4	10	7
	4	110	1028	7.30	0.59	67	1500	532	20	3	10	8
	5	90	905	8.29	0.53	69	-	-	16	3	10	9
0.390	1	110	1990	3.77	0.00	100	1500	276	0	69	69	18
	2	150	2597	2.89	0.72	61	1500	360	20	11	21	15
	3	140	2598	2.89	0.90	54	1500	360	30	8	18	15
	4	110	2309	3.25	0.90	54	1500	319	30	7	18	16
	5	90	2048	3.66	0.81	57	-	-	25	6	19	18
0.444	1	110	1046	7.17	0.00	100	1500	408	0	57	57	10
	2	150	1791	4.19	0.55	68	1500	512	22	7	14	10
	3	140	1756	4.27	0.77	59	1500	503	26	5	13	11
	4	110	1567	4.79	0.76	59	1500	451	25	4	13	12
	5	90	1404	5.34	0.69	62	-	-	21	4	15	13
0.604	1	110	2048	3.66	0.00	100	1500	441	0	126	126	19
	2	150	2437	3.08	0.73	60	1500	573	21	7	20	14
	3	140	2431	3.09	0.87	55	1500	571	30	4	16	14
	4	110	2250	3.33	0.87	55	1500	506	29	3	16	16
	5	90	2084	3.60	0.81	57	-	-	25	3	18	18

(b) Sequence #6

l	Run no. i	q units	t(q) manhrs	C	f	$f_{\%}$	t_b manhrs	q+s units	$q_i+\alpha_{i+1}$ units	$\hat{T}_{1,i}$ manhrs	$T_{1,i}$ manhrs	$T_{avg,i}$ manhrs
0.362	1	200	1354	5.54	0.00	100	3000	1248	0	29	29	7
	2	60	676	11.09	0.65	64	1500	421	7	4	14	10
	3	40	554	13.53	0.39	76	3000	908	9	4	13	11
	4	300	1766	4.25	0.34	79	-	-	3	4	17	6
0.390	1	200	2865	2.62	0.00	100	3000	647	0	69	69	14
	2	60	1516	4.95	0.98	51	1500	218	10	9	27	22
	3	40	1284	5.84	0.57	67	3000	387	14	8	24	24
	4	300	3702	2.03	0.49	71	-	-	4	7	36	12
0.444	1	200	1901	3.95	0.00	100	3000	1068	0	57	57	10
	2	60	1081	6.94	0.82	57	1500	331	9	5	20	16
	3	40	919	8.16	0.50	70	3000	701	12	5	18	18
	4	300	2888	2.60	0.44	74	-	-	4	5	28	10
0.604	1	200	2596	2.89	0.00	100	3000	1392	0	126	126	13
	2	60	1713	4.38	0.93	52	1500	343	10	5	30	24
	3	40	1549	4.84	0.60	66	3000	825	14	4	24	29
	4	300	3067	2.45	0.54	69	-	-	5	4	44	10

Table 3.18. Learning-Forgetting phenomenon on different production sequences.

(a) Sequence #7

l	Run no. i	q units	t(q) manhrs	C	f	$f_{\%}$	t_b manhrs	q+s units	$q_i+\alpha_{i+1}$ units	$\hat{T}_{1,i}$ manhrs	$T_{1,i}$ manhrs	$T_{avg,i}$ manhrs
0.362	1	200	1397	5.37	0.00	100	4500	2007	0	29	29	7
	2	90	832	9.01	0.67	63	3000	1022	3	4	17	9
	3	300	1771	4.24	0.45	73	-	-	5	4	16	6
0.390	1	210	2952	2.54	0.00	100	4500	958	0	69	69	14
	2	90	1810	4.14	0.99	50	3000	468	4	9	36	19
	3	300	3716	2.02	0.66	63	-	-	6	7	32	12
0.444	1	210	2004	3.74	0.00	100	4500	1745	0	57	57	10
	2	90	1279	5.86	0.85	56	3000	822	4	5	29	14
	3	300	2903	2.58	0.58	67	-	-	5	5	25	10
0.604	1	210	2646	2.83	0.00	100	4500	2581	0	126	126	13
	2	90	1925	3.90	0.95	52	3000	1008	4	5	48	20
	3	300	3073	2.44	0.68	62	-	-	6	4	38	10

(b) Sequence #8

l	Run no. i	q units	t(q) manhrs	C	f	$f_{\%}$	t_b manhrs	q+s units	$q_i+\alpha_{i+1}$ units	$\hat{T}_{1,i}$ manhrs	$T_{1,i}$ manhrs	$T_{avg,i}$ manhrs
0.362	1	200	1354	5.54	0.00	100	1500	644	0	29	29	7
	2	235	1598	4.69	0.65	64	1500	732	24	4	9	6
	3	165	1338	5.61	0.74	60	-	-	31	3	8	7
0.390	1	200	2865	2.62	0.00	100	1500	399	0	69	69	14
	2	235	3443	2.18	0.98	55	1500	489	35	9	17	13
	3	165	2968	2.53	0.99	50	-	-	60	6	14	14
0.444	1	200	1901	3.95	0.00	100	1500	558	0	57	57	10
	2	235	2282	3.29	0.82	57	1500	658	30	5	12	9
	3	165	1968	3.81	0.95	52	-	-	38	4	11	10
0.604	1	200	2596	2.89	0.00	100	1500	633	0	126	126	13
	2	235	2918	2.57	0.93	52	1500	766	34	5	15	11
	3	165	2638	2.84	0.99	50	-	-	48	3	12	12

Table 3.19. Learning-Forgetting phenomenon on different production sequences.

(a) Sequence #9

l	Run no. i	q units	t(q) manhrs	C	f	$f_{\%}$	t_b manhrs	q+s units	$q_i+\alpha_{i+1}$ units	$\hat{T}_{1,i}$ manhrs	$T_{1,i}$ manhrs	$T_{avg,i}$ manhrs
0.362	1	220	1439	5.21	0.00	100	3000	1286	0	29	29	7
	2	180	1301	5.76	0.68	62	7500	3761	8	4	13	7
	3	150	1132	6.63	0.63	65	1500	567	1	3	23	7
	4	50	685	10.94	0.57	67	-	-	19	3	10	10
0.390	1	220	3037	2.47	0.00	100	3000	679	0	69	69	14
	2	180	2787	2.69	0.99	50	7500	1629	13	8	25	15
	3	150	2414	3.11	0.96	51	1500	333	1	7	53	16
	4	50	1602	4.68	0.84	56	-	-	27	6	19	21
0.444	1	220	2091	3.59	0.00	100	3000	1109	0	57	57	10
	2	180	1891	3.97	0.87	55	7500	3378	9	5	20	10
	3	150	1668	4.50	0.81	57	1500	479	1	4	42	11
	4	50	1112	6.74	0.73	60	-	-	23	3	14	15
0.604	1	220	2695	2.78	0.00	100	3000	1455	0	126	126	12
	2	180	2547	2.95	0.97	51	7500	6100	11	5	29	13
	3	150	2322	3.23	0.91	53	1500	531	1	3	83	15
	4	50	1776	4.22	0.83	56	-	-	27	3	17	23

(b) Sequence #10

l	Run no. i	q units	t(q) manhrs	C	f	$f_{\%}$	t_b manhrs	q+s units	$q_i+\alpha_{i+1}$ units	$\hat{T}_{1,i}$ manhrs	$T_{1,i}$ manhrs	$T_{avg,i}$ manhrs
0.362	1	180	1266	5.92	0.00	100	3000	1209	0	29	29	7
	2	200	1384	5.42	0.62	65	1500	654	7	4	14	7
	3	110	1055	7.11	0.66	63	1500	541	25	3	9	8
	4	110	1013	7.40	0.54	69	-	-	17	3	10	8
0.390	1	180	2687	2.79	0.00	100	3000	615	0	69	69	15
	2	200	2949	2.54	0.93	53	1500	411	10	9	27	14
	3	110	2373	3.16	0.99	50	1500	329	38	7	17	16
	4	110	2269	3.31	0.83	56	-	-	27	6	19	17
0.444	1	180	1840	4.08	0.00	100	3000	1025	0	57	57	10
	2	200	1979	3.79	0.79	58	1500	571	8	6	21	10
	3	110	1605	4.67	0.84	56	1500	461	31	4	12	11
	4	110	1545	4.86	0.70	61	-	-	21	4	14	12
0.604	1	180	2489	3.01	0.00	100	3000	1326	0	126	126	14
	2	200	2643	2.84	0.89	54	1500	651	9	5	31	13
	3	110	2286	3.28	0.95	52	1500	519	35	3	14	16
	4	110	2227	3.37	0.82	57	-	-	26	3	17	16

Table 3.20. Learning-Forgetting phenomenon on different production sequences.

(a) Sequence #11

l	Run no. i	q units	t(q) manhrs	C	f	$f_{\%}$	t_b manhrs	q+s units	$q_i+\alpha_{i+1}$ units	$\hat{T}_{1,i}$ manhrs	$T_{1,i}$ manhrs	$T_{avg,i}$ manhrs
0.362	1	230	1480	5.07	0.00	100	1500	689	0	29	29	6
	2	145	1234	6.08	0.70	62	4500	1921	28	4	9	7
	3	150	1141	6.57	0.61	66	1500	570	3	3	18	7
	4	75	836	8.97	0.57	67	-	-	19	3	10	9
0.390	1	230	3120	2.40	0.00	100	1500	438	0	69	69	14
	2	145	2734	2.74	0.99	50	4500	922	45	8	16	15
	3	150	2442	3.07	0.94	52	1500	338	4	7	37	16
	4	75	1907	3.93	0.85	55	-	-	28	6	19	19
0.444	1	230	2186	3.43	0.00	100	1500	605	0	57	57	10
	2	145	1824	4.11	0.90	54	4500	1659	32	5	12	10
	3	150	1683	4.46	0.78	58	1500	483	3	4	29	11
	4	75	1313	5.71	0.73	60	-	-	23	4	14	13
0.604	1	230	2743	2.73	0.00	100	1500	692	0	126	126	12
	2	145	2506	2.99	0.99	50	4500	2455	38	5	14	14
	3	150	2339	3.21	0.90	54	1500	537	4	4	49	15
	4	75	1989	3.77	0.84	56	-	-	27	3	17	19

(b) Sequence #12

l	Run no. i	q units	t(q) manhrs	C	f	$f_{\%}$	t_b manhrs	q+s units	$q_i+\alpha_{i+1}$ units	$\hat{T}_{1,i}$ manhrs	$T_{1,i}$ manhrs	$T_{avg,i}$ manhrs
0.362	1	120	1221	6.14	0.00	100	1500	597	0	29	29	7
	2	150	1008	7.44	0.60	66	4500	1804	21	5	10	8
	3	150	1017	7.38	0.52	70	3000	1100	3	4	18	8
	4	180	1378	5.44	0.53	69	-	-	6	3	15	7
0.390	1	170	2595	2.89	0.00	100	1500	359	0	69	69	15
	2	105	2257	3.32	0.90	54	4500	816	30	9	18	17
	3	125	2187	3.43	0.80	58	3000	529	3	8	39	17
	4	200	2932	2.56	0.78	58	-	-	8	7	30	14
0.444	1	170	1782	4.21	0.00	100	1500	510	0	57	57	10
	2	105	1538	4.88	0.77	59	4500	1526	25	6	13	12
	3	125	1522	4.93	0.68	62	3000	907	3	5	31	12
	4	200	1963	3.82	0.67	63	-	-	7	4	23	10
0.604	1	170	2434	3.08	0.00	100	1500	572	0	126	126	14
	2	105	2218	3.38	0.87	55	4500	2208	29	6	16	16
	3	125	2178	3.44	0.79	58	3000	1144	3	4	52	17
	4	200	2634	2.85	0.78	58	-	-	8	3	34	13

Table 3.21. Learning-Forgetting phenomenon on different production sequences.

(a) Sequence #13

l	Run no. i	q units	$t(q)$ manhrs	C	f	$f_{\%}$	t_b manhrs	$q+s$ units	$q_i+\alpha_{i+1}$ units	$\hat{T}_{1,i}$ manhrs	$T_{1,i}$ manhrs	$T_{avg,i}$ manhrs
0.362	1	120	977	7.67	0.00	100	6000	2613	0	29	29	8
	2	240	1527	4.91	0.51	70	4500	2077	2	5	21	6
	3	130	1046	7.17	0.71	61	1500	538	3	3	17	8
	4	110	1012	7.41	0.54	69	-	-	17	3	10	8
0.390	1	120	2098	3.57	0.00	100	6000	1098	0	69	69	17
	2	240	3216	2.33	0.75	75	4500	1015	2	11	47	13
	3	130	2249	3.33	0.98	51	1500	314	7	7	31	17
	4	110	2248	3.34	0.80	58	-	-	25	6	19	17
0.444	1	120	1468	5.11	0.00	100	6000	2237	0	57	57	12
	2	240	2296	3.27	0.65	64	4500	1824	2	7	37	10
	3	130	1558	4.82	0.93	52	1500	449	3	4	29	12
	4	110	1538	4.88	0.69	62	-	-	20	4	15	12
0.604	1	120	2120	3.54	0.00	100	6000	3564	0	126	126	18
	2	240	2798	2.68	0.76	59	4500	2721	2	7	69	12
	3	130	2217	3.38	0.99	50	1500	496	5	4	45	16
	4	110	2216	3.38	0.79	58	-	-	24	3	18	17

(b) Sequence #14

l	Run no. i	q units	$t(q)$ manhrs	C	f	$f_{\%}$	t_b manhrs	$q+s$ units	$q_i+\alpha_{i+1}$ units	$\hat{T}_{1,i}$ manhrs	$T_{1,i}$ manhrs	$T_{avg,i}$ manhrs
0.362	1	100	870	8.62	0.00	100	1500	481	0	29	29	9
	2	150	1088	6.31	0.47	72	1500	586	13	6	11	7
	3	150	1221	6.14	0.59	66	3000	1189	20	4	10	7
	4	200	1382	5.43	0.60	66	-	-	7	3	14	7
0.390	1	100	1877	4.00	0.00	100	1500	262	0	69	69	19
	2	150	2582	2.90	0.68	62	1500	357	19	11	22	15
	3	150	2687	2.79	0.90	54	3000	615	30	8	18	15
	4	200	2949	2.54	0.93	53	-	-	10	7	27	14
0.444	1	100	1327	5.65	0.00	100	1500	390	0	57	57	13
	2	150	1758	4.27	0.60	66	1500	503	16	7	16	11
	3	150	1662	4.51	0.76	59	3000	1014	25	5	13	10
	4	200	1999	3.75	0.75	60	-	-	9	4	20	10
0.604	1	100	1973	3.80	0.00	100	1500	417	0	126	126	20
	2	150	2428	3.09	0.70	61	1500	569	19	8	21	14
	3	150	2486	3.02	0.87	55	3000	1324	29	4	16	14
	4	200	2643	2.84	0.89	54	-	-	9	3	31	13

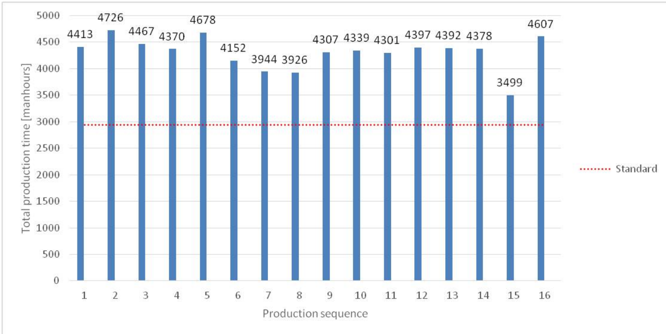
Table 3.22. Learning-Forgetting phenomenon on different production sequences.

(a) Sequence #15

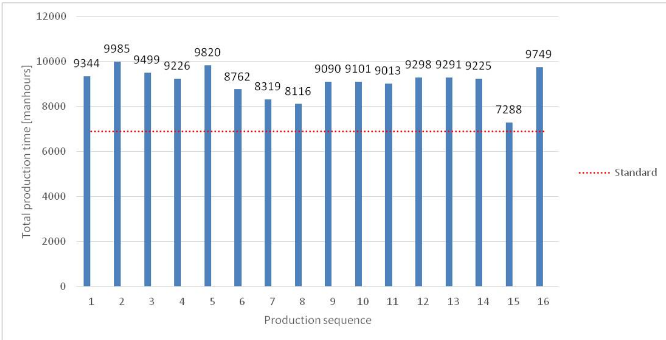
l	Run no. i	q units	t(q) manhrs	C	f	$f_{\%}$	t_b manhrs	q+s units	$q_i+\alpha_{i+1}$ units	$\hat{T}_{1,i}$ manhrs	$T_{1,i}$ manhrs	$T_{avg,i}$ manhrs
0.362	1	300	1754	4.28	0.00	100	4500	2201	0	29	29	6
	2	300	1768	4.24	0.79	58	-	-	4	4	17	6
0.390	1	300	3669	2.04	0.00	100	4500	1114	0	69	69	12
	2	300	3749	2.00	0.99	50	-	-	11	75	26	12
0.444	1	300	2851	2.63	0.00	100	4500	1962	0	57	57	10
	2	300	2879	2.61	0.99	50	-	-	5	5	27	10
0.604	1	300	3048	2.46	0.00	100	4500	2963	0	126	126	10
	2	300	3066	2.45	0.99	50	-	-	7	4	36	10

(b) Sequence #16

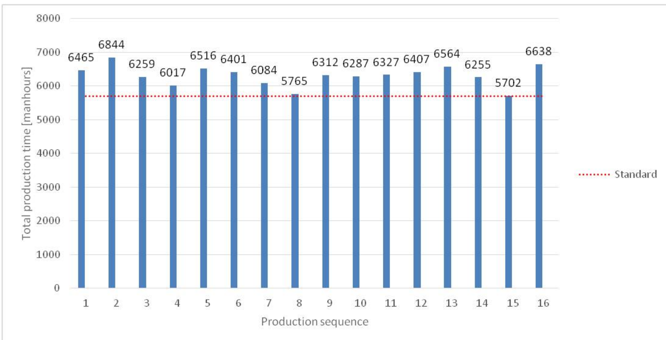
l	Run no. i	q units	t(q) manhrs	C	f	$f_{\%}$	t_b manhrs	q+s units	$q_i+\alpha_{i+1}$ units	$\hat{T}_{1,i}$ manhrs	$T_{1,i}$ manhrs	$T_{avg,i}$ manhrs
0.362	1	200	1354	5.54	0.00	100	3000	1248	0	29	29	7
	2	110	964	7.78	0.65	64	1500	511	7	4	14	8
	3	70	784	9.56	0.51	70	1500	454	15	4	11	9
	4	40	569	13.19	0.44	74	4500	1584	11	3	12	11
	5	180	1275	5.88	0.34	79	-	-	2	3	20	7
0.390	1	200	2865	2.62	0.00	100	3000	647	0	69	69	14
	2	110	2103	3.57	0.98	51	1500	291	10	9	27	17
	3	70	1785	4.20	0.75	59	1500	250	22	7	20	19
	4	40	1336	5.61	0.65	64	4500	642	17	7	22	23
	5	180	2709	2.77	0.51	70	-	-	2	7	43	15
0.444	1	200	1901	3.95	0.00	100	3000	1068	0	57	57	10
	2	110	1462	5.13	0.82	57	1500	424	9	5	20	12
	3	70	1240	6.05	0.65	64	1500	368	19	4	15	14
	4	40	945	7.93	0.68	68	4500	1267	14	4	17	17
	5	180	1732	4.33	0.73	73	-	-	2	4	34	10
0.604	1	200	2596	2.89	0.00	100	3000	1392	0	126	126	13
	2	110	2120	3.54	0.93	52	1500	463	10	5	30	18
	3	70	1909	3.93	0.76	59	1500	398	22	4	19	21
	4	40	1587	4.72	0.68	62	4500	1721	18	3	21	27
	5	180	2503	3.00	0.56	68	-	-	3	3	59	14



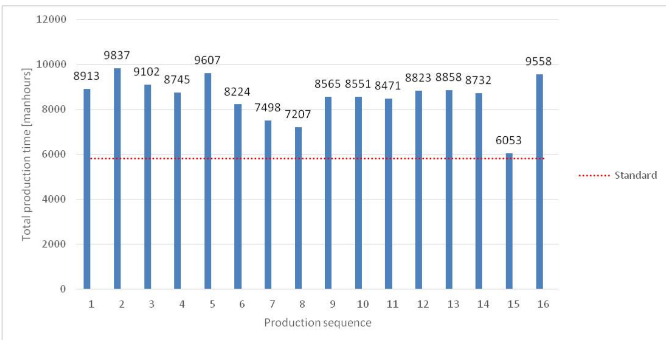
(a) l=0.362



(b) l=0.390



(c) l=0.444



(d) l=0.604

Figure 3.34. Total production time for each production sequence.

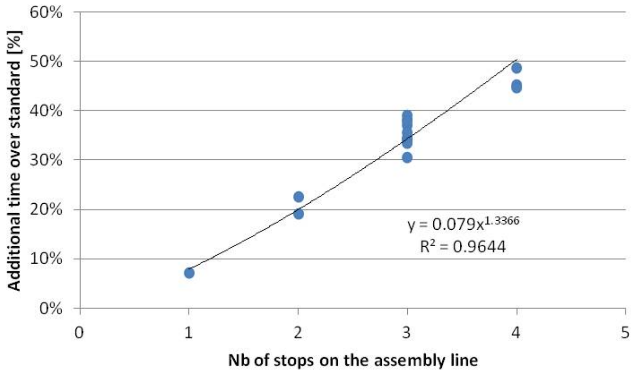


Figure 3.35. Production breaks effect on the additional percentage over the standard production time.

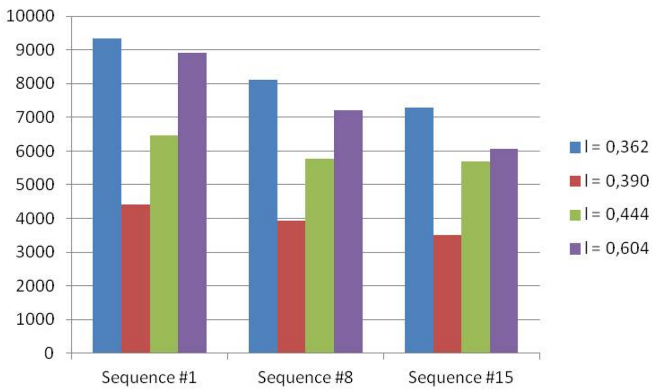


Figure 3.36. Production system #3 total time behaviour at learning constant variation [manhours].

Chapter 4

Sustainable optimization of production planning

During a construction Project, in order to avoid extra-costs, disruptions or client charges for delays in work completion, the milestones on critical path have to be strictly followed by all of the Supply Chain actors which, basically, are:

- Design department;
- Purchasing department;
- Production department;
- Installation Site.

It comes clear that the activities involving every department lead to manage significant trade-offs, since each construction project, due to its peculiarities, has plenty of custom elements to be designed and purchased with low repetitiveness rates and engineer to order components to be produced. Stated that all of the process has to be pulled by the contractual due dates, and that a batch of elements of the same type causes no setup costs or slowdowns, it becomes relevant to optimize the production on the assembly line without compromising site activities. In fact, in a curtain wall building production, the same element can be installed into different floors or elevations, which have different installation priorities, e.g. by referring to picture 4.1, the production line would like to produce per typologies (first green product family, red one and so on) in order to optimize assembly rates, while different codes belonging to the same product family can have a different location on the facade: it is desirable to produce panels 4 and 59 in the same production batch, but they have to be installed onto 3rd and 7th floors, respectively. Handling and logistics on site are tough issues: packs can be moved onto

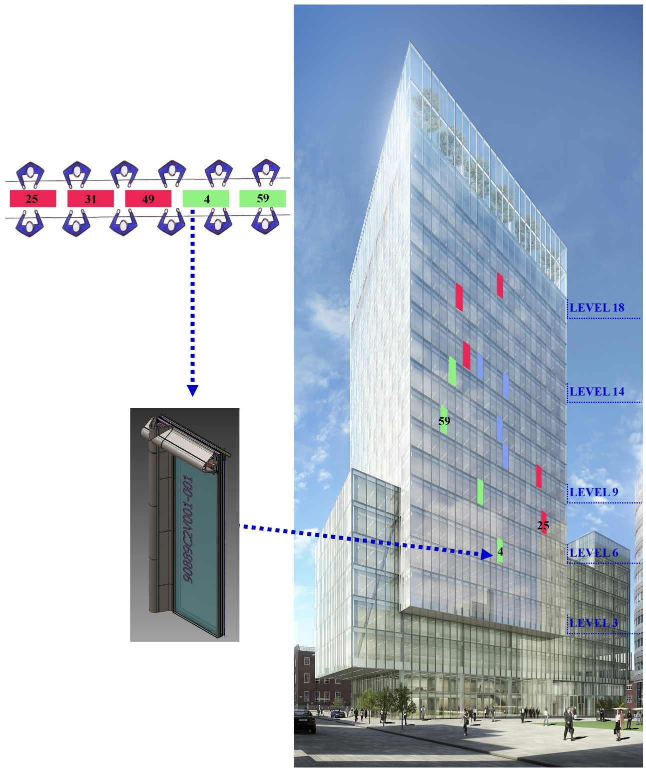


Figure 4.1. Trade-off between production and site needs.

floors just by tower cranes, hoists or mono-rails, hence it is not possible to deliver a crate with elements that have to be installed into different floors, since the pack cannot be wrapped again to move it to upper levels for time and safety reasons. Moreover, once the pack has been opened on site in order to install one element, then also the balance of the pieces contained by the crate has to be installed soon to avoid damages that frequently occur, thus generating the arise of non-conformities that turn into extra costs for the re-ordering, re-production, re-handling and consequent scrapping of the ruined materials. Most construction sites do not have huge space to stock large elements, so the company cannot deliver much more items than the ones specified in the delivery schedule, unless stockpiled into the production plant or into an external warehouse, thus generating inventory costs. On the other side, if the produced items do not meet site installation demand on a given day, then delays in the contractual handover of part of the project may be caused, with the risk of incurring in penalty costs.

A construction PBE, as a common manufacturing firm, has to improve the economic result by maximizing the production of items, but the main difference is that each element has a unique location on the building to be handover to the client within specific delivery dates set into the contractual program. For this reason, number of transports in a project for a construction PBE is strictly linked to the production sequence and it has to be taken into account not only during the scheduling, but also during the planning phase, since every unit has to come on site by mirroring the installation program or with a minimum acceptable slack time: unless the project budget allows the usage of an external warehouse or the company is equipped with a large storage area, the stocking space on site is limited. Therefore installation scheduling has to be observed and logistically organized on a few daily basis. Hence, to green the PBE supply chain from the environmental point of view without compromising site activities, it has to be considered that production optimization has direct implication on the filling-up of containers or trucks. In turn, higher fulfillment rates result in a smaller number of means of transport to site, therefore less consequent pollutant emissions, which means environment protection and supply chain greening.

The social theme of the Triple Bottom Line (TBL) can be introduced into the production planning through the learn-forget curve model, suitable for limited productions. Workers, in fact, improve their performances according to the production sequence, which mixes up the various typologies of elements by taking into account the due dates stated on the project program. Thus, one typology can be produced in more than one batch during the time horizon by alternating it with the other typologies of the building. Hence production phase in construction PBEs can be defined as discontinuous, subjected to not only learning but also to forgetting phenomenon. By inserting the learning-forgetting curve into the production planning model, more realistic cycle times can be calculated and managed, thus reducing the work stress of the personnel thanks to feasible plans and making factory environment more friendly, therefore improving performances. Moreover the planning on the horizon shows the real production capacity of the assembly line, by making more reliable forecasts during the project planning definition.

In this chapter, the first paragraph is introductory in the constraint programming, which is the paradigm that has been used for the achievement of the model; section 4.2 describes in detail the sustainable optimization tool for production this thesis is focused on; in the last section computational time of the model is assessed.

4.1 Constraint Programming

The *Constraint Programming* (CP) is a programming paradigm wherein relations between variables are stated in the form of constraints, which do not specify a step or sequence of steps to execute, but rather the properties of a solution to be found (Rossi et al., 2006). CP divides the coding into two phases: modeling and solving. During the first one, the problem is being modeled through constraints on variables, which can be non-linear, as the objective function may be. The developer can then focus on the description of the properties required by the solution, by introducing relations among variables, rather than on the definition of an algorithm to generate the solution itself. During the solving phase, in fact, the developer can rely on a *constraint solver* which reduces the search space by pruning values from the variable domains which cannot appear in any solution. Decades of research on the best solution search strategy have been implemented into CP softwares, therefore by offering advanced and powerful solvers. It is important to emphasize an important property of constraints: they are independent of each other and interact only through incremental variables. The resulting flexibility greatly simplifies the definition of new constraints and objectives since the differentiable objects can be implemented in isolation, and makes it easy to add constraints in a model without affecting the rest of the model and the search. As underlined by Banaszak et al. (2009), thanks to their rich language, constraint-based systems are suitable for the modeling of complex problems, such us the ones faced during an enterprise decision process. By comparing the CP models to other methodologies, e.g. genetic algorithms, simulated annealing or tabu search, they are easier to be modified and updated, characteristic that makes them quickly adjustable to context variations for which they have been created and makes them extensible to similar situations with the minimum tuning. In order to enhance the power of obtaining nearly optimal solutions in reduced computational time, it is possible to introduce *local search* strategies after having obtained a good solution from the main CP program. The *Large Neighborhood Search* (LNS), specifically, introduced by Shaw (1998) can hybridize the CP and local search with optimal performances (Van Hentenryck and Michel, 2005). LNS consists in an iterative process that, by starting from an admissible solution, destroys at each iteration part of the current solution by using a stated definition of closeness and it optimizes again, in order to hopefully improve the result. The *neighborhood procedure* chooses a set of variables, so called *free-variables*, that have to be assigned again, while the remaining variables do not change respect to the current solution; the model structure is saved, so that it is possible to always generate admissible solutions. The problem presented in this research has been modeled in its complexity according to the Constraint Programming nature (par. 4.2, and then it has been solved with an hybrid approach CP + LNS. COMET package has been used both for the modeling and solving phases.

4.2 The Model

The elements or panels of the facade have been divided into packs that contain a certain number of them; each pack of a construction project is assigned with a unique code number, which is associated with an *installation date*,

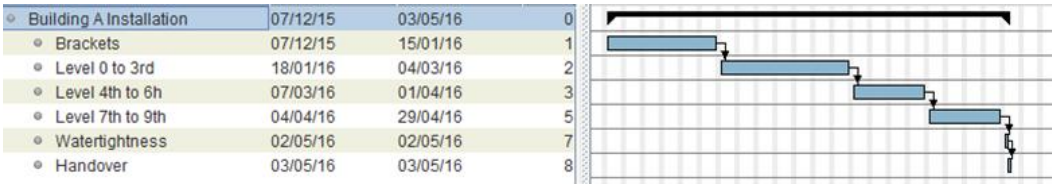


Figure 4.2. Gantt schedule of a curtain wall project

set according to the Gantt schedule handover of the levels (whose extract is given in figure 4.2 as an example), and a *due date*, which is the very last date the element can be shipped in order not to generate delays on requirements at the construction site. The decision variables of the model are therefore the period within the planning horizon H during which the pack i should be produced and the period in which it should be shipped; one more decision variable sets the period in which a pack already on stock, due to the production been made in previous horizons, is convenient to be shipped. The three variables are set to 0 if element i is not conveniently produced in H. Auxiliary variables are introduced to easily manage the objective function and constraints.

Packs are given as an input to the model since they are the minimum handling unit for truck loads and for site also. Their creation is being done according to:

- level or elevation of installation of the panel: packs have to be lifted to floors all at once to avoid extra handing on site which is a time-consuming activity subject to availability of logistics in terms of space and equipment, and dangerous since it enhances the probability of causing damages to the materials;
- geometry of the panels: packs should contain panels with similar dimensions in order to be resistant to transport and handing stress (geometry grouping often overlaps with family product one);
- capacity and characteristics of handling and lifting equipment in the production plant and installation site.

An example of pack definition can be seen in image 4.3, where different colours point out different packs. Packs in the picture are at the executive stage of the project, since the production orders can be created just once the packing list has been clearly defined. At the preliminary stage for which this model has been thought, pack definition is less precise since it is not possible to know well in advance all of the variables of the project, e.g. to know where to stock materials which is close to the installation process (which is the maximum capacity and dimensions of the hoist and of tower crane? do the packs have to be lifted at levels, and if so, where? Which is the maximum load capacity of the inter-floor slab?), but the process follows the same logic.

4.2.1 Model variables

Model decision and auxiliary variables can substantially be grouped as follows:

1. production variables: they define the period in which an element has to be produced in time horizon H;
2. shipment variables: they define the period in which an element has to be shipped in time horizon H;
3. learning-forgetting variables: they embed the learning-forgetting model (see chapter 3) into the production time required for each panel to be assembled;
4. setup variables: they take into account the setup change on the assembly line when different family products have to be produced;
5. transport variables: they calculate the loss of space in a mean of transport;

All of the variables are in Italic style in model equations and are reported in table 4.1, where the group of belonging has been reported in the first column.

As for the *production variables*, the decision one is *period[i]*, which assigns to every pack to be produced the period in which to assemble it; while the second group has two decision variables which are the shipment periods, *shipment[i]*, of packs produced in horizon H, and the shipment period of the packs which are on stock in the plant warehouse since they have been produced in previous horizons, *shipOnhand[i]*. An example of how decision variables work can be seen in picture 4.4, where both packs 1 and 2 have *due date* in period 8, by meaning that they have to be shipped within this period and their installation period is 10, so at that time production, transport and stock related costs are going to cease; P is the production period of pack i, S is the shipment period of pack i, OH is the shipment period of pack i stack in production plant,*ip* indicates inventory period in production plant, *is* indicates inventory period on site, t is the transport lead time.

According to the picture, result for the first horizon is:

- period[pack 1] = 2;
- period[pack 2] = 4;
- shipment[pack 2] = 5.

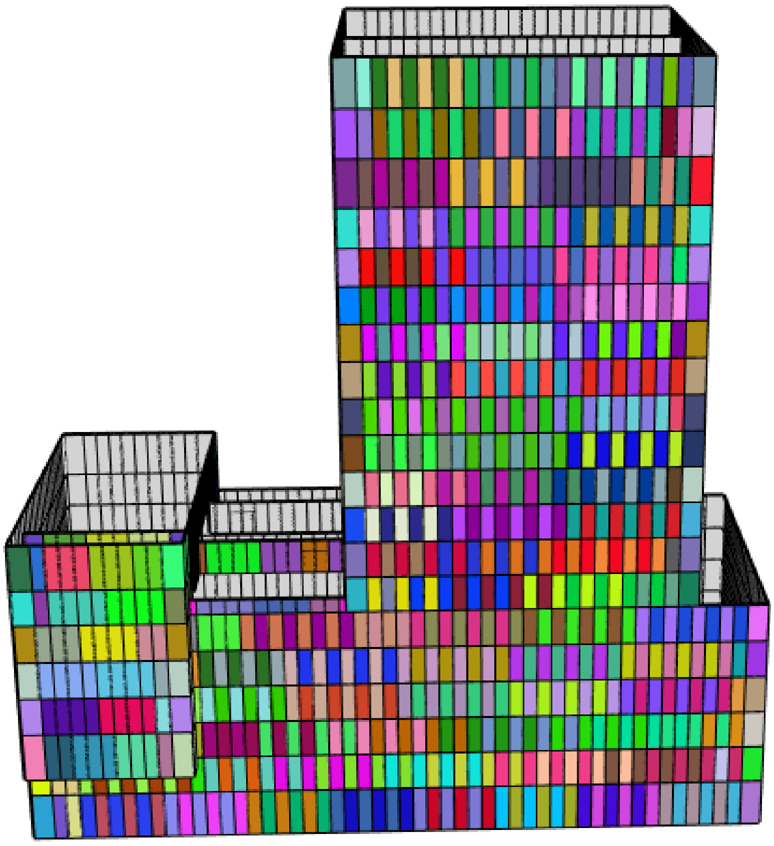


Figure 4.3. Building facade elevation divided into packs (courtesy of Permasteelisa Group).

Horizon	1					2					3				
Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Pack 1		P	ip	ip	ip	OH	t	is	is	I					
Pack 2				P	S	t	is	is	is	I					

Figure 4.4. Example of production of 2 packs.

Table 4.1. Model main variables. N is the set of packs of the project, P is the set of the elements on stock in the production plant, H the set of planning periods, H* the number of periods in the planning horizon, M the set of different family products to be assembled, C the set of different types of unit loads, U the set of different setup classes, L the set of the total floors of the building.

Group	**Variable**	**Range**	**Description**
1	*period[i]*	$i \in N$	Production period of pack i
1	*prod[i,j]*	$i \in N, j \in H$	1 if i is produced in j, 0 otherwise
2	*shipment[i]*	$i \in N$	Shipment period of pack i
2	*delivery[i,j]*	$i \in N, j \in H$	1 if i is produced in j, 0 otherwise
2	*shipOnhand[i]*	$i \in P$	Shipment period of pack i stocked in the plant
2	*onhandGo[i, j]*	$i \in P$, $j \in H$	1 if i is produced in j, 0 otherwise
3	*prodType[k,j]*	$k \in M, j \in H$	Qty of family k produced in j
3	*t[k,j]*	$k \in M$, $j \in H$	Total assembly time for family k in j
3	*sumT[j]*	$j \in H$	Total production time in period j
3	*prodSeq[k,v]*	$k \in M$, $v \in [0..H^*]$	1 if k is assembled in v, 0 otherwise; v=0 if previous horizons
3	*lf[k]*	$k \in M$, $k \in M$	Learning-forgetting sequence in horizon
3	*tf[k]*	$k \in M$, $k \in M$	Time interval for forgetting break
4	*setup[u,j]*	$u \in U, j \in H$	1 if parts of setup class u are assembled in j, 0 otherwise
4	*sumSu[j]*	$j \in H$	Total set-up time in period j
5	*ltl[c,j]*	$c \in C$, $j \in H$	Total truck space lost by unit load class
1 & 3	*unprod[j]*	$j \in H$	Total idle time due to unproduction in j
2 & 5	*unload[j]*	$j \in H$	Total empty space in trucks in j
1 & 3	*overtime[j]*	$j \in H$	Total overtime in production in j

By following a rolling logic, in horizon #2, when the model starts for the second time, pack 1 is already on stock:

- shipOnhand[pack 1] = 6;
- ip[pack 1] = 3;
- is[pack 1] = 2;
- ip[pack 2] = 3;

When *Learning-forgetting variables* play the role, each element contained in pack i has to be taken into account in order to calculate the total time to produce the entire pack itself. Since packs have been previously set according to panels geometry (and so to family products), production can be optimized as long as packs belonging to the same typology k are being produced in the same period, since the learning effect can be exploited for a longer time, thus limiting the forgetting phenomenon that inevitably happens with PBEs discontinuous production system. In this contest, the best production sequence, as a 0-1 combination, is reach out through variable *prodSeq[k,v]*, which is correlated to variable *t[k,j]*, i.e. the total time spent to produce packs belonging to typology k in period j.

In PBEs, productions cost related to set-ups may be significant: due to the huge and varying dimensions of the panels, the automatic conveyor width of the assembly line must be revised several occasions. These kind of activity can take at least 4 hours to be ended, thus causing rather a long unproductive impact. For this reason, each product family of this model is associated to its set-up class, which may be shared with other product families, if possible. Variable *setup[u,j]* has then been created to assume value 1 every time the production plan encounters family products belonging to different set-up classes, so that consequently variable *sumSu[j]* sums up the number of different set-up classes carried out in order to let the model minimize them.

By reflecting the reality of the production and shipment process of a PBE, when packs have to be stacked, vertical space exploitation is sought, therefore minimizing the soil occupation. For this reason, packs have been assigned a *crate typology* so that packs with the same crate typology can be piled. As a consequence, in order to maximize means of transport fulfillment, these piles, characterized by packs which share the same kind of crating, have to be load onto the truck bed. Hence *Transport variables* are defined in range C, that is the number of different crate typologies that can be carried out throughout the building production.

4.2.2 Model input data and parameters

The user has to enter the model the data input according to the context to be faced, and they are listed in regular font in table 4.2, while table 4.3 reports all of the parameters.

These data input and parameters can be divided as follows:

1. technical project data: the user has to set the main characteristic of the project in terms of number of packs and typologies to produce;
2. programming input: the user has to set the period (e.g. week of the year) in which the computation has to start according to the Gantt project, the planning horizon to consider;
3. transport parameters: set of transport lead time;
4. production capacity input: set of the assembly line capacity over horizon;
5. mean of transport capability;
6. learning forgetting input/parameters: set of learning constant and time for total forgetting (refer to chapter 3);
7. costs;
8. weight of the activities along the supply chain.

Parameter generalInfo[i,r], as text file, transfers to the model the data as per table 4.4, so each pack i of the project is associated to the product family that is inside it, to the parameter *dueDate[i]* which is the latest date the pack can be shipped to respect installation schedule, to the number of panels inside the pack, to the level of the building in which the pack i has to be installed.

The stock status of each pack is parameterized through stockInfo[i,r], which is a text file that has to be updated each time the model rolls to the next planning horizon because it registers if and when the pack has been produced, if and when the pack has been shipped, if the pack has been installed according to the scheduled installation period. These parameters are fundamental to calculate the stock related costs and to reduce computational time through the horizons, since the model considers just the needful elements in horizon.

The feature of every pack are summarized in table 4.6, which show the way these parameters are used by the model:

- $\bar{T}_{\mathrm{k}}$ is the estimated standard production time for typology k, evaluated during the tender phase according to the number of components and assembly complexity;

Table 4.2. Model input data; M is the set of different family products to be assembled; H is the planning horizon. In first column: 1 = technical project data; 2 = programming input; 3 = transport parameter; 4 = production capability input; 5 = mean of transport capability; 6 = learning forgetting input/parameters; 7 = costs; 8 = weight of the activities along the supply chain.

Category	Input	Range	Description
1	nTypes		No. of typologies of the project
1	panels		No. of panels of the project
1	nPacks		No. of packs of the project
1	nSetup		No. of possible setups in the project
1	startLev		First level of the building
1	endLev		Last level of the building
2	start		Start period of the planning horizon
2	horizon		No. of periods in planning horizon
3	travel		Transport lead time [periods]
4	capacity		Assembly line capacity over planning horizon[minutes]
4	maxOver		Allowed production overcapacity [%]
4	timeSu		Cumulated time for set-up [minutes]
5	volume		Loading volume of the mean of transport [m^3]
6	l[k]	$k \in M$	learning constant of family product k
6	tF[k]	$k \in M$	time to produce the first unit of family product k
6	tB[k]	$k \in M$	total forgetting time of family product k
6	std		average multiplying factor for first unit production time
7	c_{up}		Cost for production loss [€/min]
7	c_{su}		Cost for line setup [€/min]
7	c_{ltl}		Cost for less than truck loading [€/m^3]
7	c_{over}		Extra cost for overtime [€/min]
7	c_{facade}		Sell price for the complete facade [€/m^2]
7	r_b		interest rate for bank capital assets [%]
7	r_h		risk rate for extra handling over time [%]
7	r_d		risk rate for material damage over time [%]
8	purchasing		weight of purchasing activity [%]
8	production		weight of production activity [%]
8	shipping		weight of shipping activity [%]
8	installing		weight of installing activity [%]
8	sqm_{avg}		average square meters per panel [m^2]
8	t_{avg}		average tender production time per panel [minutes]

Table 4.3. Model parameters. N is the set of packs of the project, M is the set of different family products to be assembled, C the set of different types of unit loads, S is the set of possible learning-forgetting sequences, B is the set of possible production interruptions.

Group	Parameter	Range	Description
1	generalInfo[i, r]	$i \in N$, $r \in [1..5]$	Packs characteristics
1	stockInfo[i, r]	$i \in N$, $r \in [1..7]$	Stock status of pack i
1	typeInfo[k, r]	$k \in M$, $r \in [1..7]$	Facade typologies characteristics
3	crateInfo[c, r]	$c \in C$, $r \in [1..5]$	Crates typologies characteristics
6	LFsequence[s, v]	$s \in S$, $l \in [0..H^*]$	Possible learning-forgetting sequences
6	seqPar[s, v]	$s \in S$, $l \in [0..H^*]$	Productive sequence with production periods
6	q_P[k]	$k \in M$	equivalent production for periods prior to $j \in H$
6	T_1[k]	$k \in M$	time to produce first unit
6	T_{1P}[k]	$k \in M$	time to produce first unit in horizon H

Table 4.4. GeneralInfo[i,r] parameter.

Pack code i	**Product family in pack i**	**Due date** dueDate[i]	**No. of units in pack i**	**Installation level of pack i**
1	1	24	5	1
2	1	24	6	1
3	2	25	8	1
4	10	26	6	2
5	6	27	7	3
..	..	..	..	..
N	k	..	..	endLev

Table 4.5. StockInfo[i,r] parameter, where: P is 1 if pack i has been produced, 0 otherwise; S is 1 if pack i has been shipped, 0 otherwise; I is 1 if pack i has been installed, 0 otherwise.

Pack code i	**P**	**P period**	**S**	**S period**	**I**	**I period**
1	1	23	1	23	1	25
2	0	0	0	0	0	31
3	0	0	0	0	0	31
4	1	26	0	26	0	30
5	1	25	1	26	1	27
..	..	..	..	..	..	..
N	..	..	..	..	..	..

- setup-class defines through a number that a typology implies a specific set-up to do, since the width of the conveyor belt has to be modified according to the width of the panels that it has to transport through the line;
- crate type points out the category of pallet that has to be used for the packaging of family k;
- Q_{std} is the foreseen quantity of panels that have to be produced to reach T_k: in coherence with the learning model, as a production batch goes on, time to produce the units decreases asymptotically to the standard time T_k with the increasing of the assembled units;
- P_{last} memorizes the last period in which family k has been produced, in order to calculate the length of the process break, which is necessary to the implementation of the forgetting phenomenon into the model production time computing;
- α indicates the level of experience remembered at the beginning of the next run, after an interruption period (please refer to chapter 3.

Table 4.6. TypeInfo[k,r] parameter, where M is the total number of family products k.

Family product k	$\bar{T}_k$ **[min]**	**Setup class**	**Crate type**	Q_{std} **[units]**	P_{last}	α **[units]**
1	294	1	1	480	25	25
2	426	1	2	375	26	3
..	..	..	..	..	..	..
M	..	..	..	..	..	..

Crate types enumerated in typeInfo[k,r] are linked to their characteristics through palInfo[c, r] matrix, which is reported in table 4.7 and whose data are necessary to the evaluation of transport costs and storage area both at the production and installation sites:

- $crate_H$ is the number of crates of typology c that can be stacked onto each other;
- $crate_P$ is the number of columns of piled packs that can be loaded in the mean of transport;
- $crate_W$ is the number of packs that can be stacked in a warehouse;
- $crate_A$ is the area occupied by the pack.

Learning-forgetting parameters LFsequence[s, v] and seqPar[s, v] are being explained in details in the following subsection 4.2.3.

Table 4.7. CrateInfo[c,r] parameter, where C is the total number of crate types c.

crate c	**$crate_H$**	**$crate_P$**	**$crate_W$**	**$crate_A$ [m^2]**
1	4	3	2	8
2	2	1	2	9
..	..	..	..	..
C	..	..	..	..

4.2.3 Model Objective Function

The objective function, shown in equation 4.1, has been build with the aim of exploiting the benefits offered by the Triple Bottom Line (TBL) concept, which, according to Elkington (1998), states that by interbreeding economic, environmental and social performances, a firm can approach a competitive long-term advantage. In the light of this, the model aims at minimizing the time losses and extra expenses that can affect the assembly line, along with the lack of saturation of the means of transports and the capital costs related to the produced/shipped items. In the objective function the different terms that allow to embrace the three dimensions of sustainability have been defined on cost bases, so that the social and environmental aspects can be compared to the economic one in an objective way. This gives the opportunity to focus simultaneously on the three aspects with the minimizing of the cost, which is the final aim to be achieved by companies. This single-objective approach have been preferred to the multi-objective one, since this latter leads to the defining of weights to give each objective which are liable to subjectivity. Moreover, through the action research interviews, it came to the surface that, because of architectural limits, Permasteelisa cannot modify transports modes nor the materials to be used, therefore the only lever that can be actually driven are production and transport optimizations from an economic point of view.

The terms composing the objective function are the following costs:

1. unproduction;
2. set-ups;
3. overtime;
4. less-than-truck load transports;
5. capital costs.

Idle time of the assembly line in terms od manhours can be calculated as per Eq. 4.2.

Time losses caused by set-ups are considered in the second term of the objective function and detailed in Eq.4.3; they happen every time there is a change in the conveyor belt width, which corresponds to a certain panel width.

Costs for the operators working overtime are calculated thanks to Eq. 4.4.

$$\begin{aligned} min \quad c_{up} \sum_{j \in H} unprod[j] + c_{su} \sum_{j \in H} sumSu[j] + c_{over} \sum_{j \in H} overtime[j] + \\ c_{ltl} \sum_{j \in H} unload[j] + \ C_{capital(unprod,ship)} \end{aligned} \tag{4.1}$$

$$unprod[j] = \text{capacity} - sumT[j] - sumSu[j] \tag{4.2}$$

$$sumSu[j] = \sum_{u \in U} \sum_{j \in H} setup[u, j] \ \text{timeSu} \tag{4.3}$$

$$unprod[j] < 0 \Rightarrow overtime[j] = sumT[j] + sumSu[j] - \text{capacity} \tag{4.4}$$

Lost space in trucks is estimated by assuming that each part type can be associated with a unit load class: this means that elements of different part types can be stacked during transport only if they belong to the same class c (column number 4 of table 4.7). For curtain wall contractors, since packs have huge dimensions, number of packs that can be stacked onto each other and number of columns inside the mean of transports can be easily calculated in a preliminary way, thus when having a set of packs ready for the shipment, the number of them that fulfill the truck is evaluated by the modulo operator % as in Eq. 4.5, where crate_H is the number of crates that is possible to stack by exploiting the height of the truck, while crate_P is the number of piles that can be contained in the length of the truck. Finally the total loss of space is obtained as a percentage of the volume of the mean of transport, as per Eq. 4.6.

$$ltl[c, j] = (\sum_{j \in H} \sum_{i \in N} \sum_{c \in C} delivery[i, j] \% (\text{crate}_\text{H} \cdot \text{crate}_\text{P}) \tag{4.5}$$

$$unload[j] = \text{volume}(1 - \frac{ltl[c, j]}{\text{crate}_\text{H} \cdot \text{crate}_\text{P}}) \tag{4.6}$$

The last term of the objective function gives evidence to all of the hidden costs of capital immobilization (4.8) which are strongly connected to the contractual agreement with the client. The most frequent kind of contracts in the curtain wall market are:

A. *job order working progress*: the company is paid by the client by steps as the processes Design, Production, Shipment, Installation are complete;

B. *at work completion*: the company is paid by the client once the installation is complete.

If the company has to face the first contract A, then each phase of the Project process has to be given a percentage weight, so that a capital cost for each step can be calculated by the program and taken into account in the objective function. For this reason an interest rate r has to be set, according to its three components chosen by the user:

$$\mathrm{r} = \mathrm{r_b} + \mathrm{r_h} + \mathrm{r_d} \tag{4.7}$$

where, as per table 4.2: the first term $\mathrm{r_b}$ refers to the bank interest rate for the financial loan or to gain interest for an alternative investment; the second item $\mathrm{r_h}$ is a risk rate that takes into account extra handling of the stock material over time, since the installation goes up floor-by-floor and trucks may host packs belonging to different floors, so packs of the same floor can be stacked in different locations, thus implying extra-handling; the third term $\mathrm{r_d}$ represents the risk rate for damages that the material can undergo over time (e.g. detriment caused by weather exposure, damages crated by handling, accidents...).

The total capital cost is formed by three parts, as per Eq. 4.8: the cost related to unproduction $\mathrm{cap_{unprod}}$, the one related to the missing of the shipment activity $\mathrm{cap_{unship}}$ and the last one which is linked to the postponement of installation process, $\mathrm{cap_{uninstall}}$.

The capital cost associated to the unproduction of the line is calculated thanks to Eq. 4.9, since the idle time of the assembly line prevents the company for being paid for the production of the units that could have been assembled if the operators would not have stopped.

$$C_{capital(unprod,unship)} = cap_{unprod} + cap_{unship} + cap_{uninstall} \tag{4.8}$$

$$cap_{unprod} = (\mathrm{purchasing}+\mathrm{production}) \cdot \mathrm{c_{facade}} \cdot \mathrm{r} \cdot \sum_{j \in H} unprod[j] \frac{\mathrm{sqm_{avg}}}{\mathrm{t_{avg}}} \tag{4.9}$$

By following the same logic, inventory cost in production and at site can be thought as the postponement payment by the client because of unshipping and uninstalling a certain number of square meters , respectively Eqs. 4.10 and 4.11, where GeneralInfo[i,4] indicates the quantity of panels inside pack *i*, as per table 4.4. For cap_{uninst} computing, it has been assumed that 2 weeks for handling are default and unavoidable costs.

$$\begin{aligned} cap_{unship} = \sum_{i \in N} (shipment[i] - period[i]) \mathrm{sqm_{avg}}\ \mathrm{GeneralInfo[i,4]} \cdot \\ \cdot \mathrm{shipping} \cdot \mathrm{c_{facade}} \cdot \mathrm{r} \end{aligned} \tag{4.10}$$

$$cap_{uninstall} = \sum_{i \in N} (\text{InstallDate[i]} - shipment[i] - \text{travel} - 3)\text{sqm}_{\text{avg}} \cdot \\ \cdot \text{GeneralInfo[i,4]} \cdot \text{installing} \cdot \text{c}_{\text{facade}} \cdot \text{r} \quad (4.11)$$

Contract typology B sets the payments from the client at the installation completion phase. For this reason, Eqs. 4.9-4.11 are replaced by Eqs. 4.13-4.15: capital cost is not represented by the lack of payment at each stage of the process but as the financial immobilization of the assets for the phases prior to installation and the payment postponement at the installation. Activities involved are taken into account into different moments respect to contract A, e.g. since the cost of the unproduction doesn't imply a lack of payment by the client, its value resides only in the financial exposure the company faced for the purchasing of the raw materials, plus their extra handling or risk of damage over time, hence in Eq. 4.13 the only activity impacting is the purchasing one. Moreover, rate r has to be integrated with an additional risk rate r_f (Eq. 4.12) that represents the negative cash flow that the firm has to face throughout all of the processes, until the installation one.

$$\text{r} = \text{r}_\text{b} + \text{r}_\text{h} + \text{r}_\text{d} + \text{r}_\text{f} \quad (4.12)$$

$$cap_{unprod} = \text{purchasing} \cdot \text{c}_{\text{facade}} \cdot \text{r} \cdot \sum_{jinH} unprod[j] \frac{\text{sqm}_{\text{avg}}}{\text{t}_{\text{avg}}} \quad (4.13)$$

$$cap_{unship} = \sum_{i \in N, c \in C} (shipment[i] - period[i])\text{sqm}_{\text{avg}} \ \text{GeneralInfo[i,4]} \cdot \\ \cdot \text{producing} \cdot \text{c}_{\text{facade}} \cdot \text{r} \quad (4.14)$$

$$cap_{uninst} = \sum_{i \in N, c \in C} (\text{InstallDate[i]} - shipment[i] - \text{travel} - 3)\text{sqm}_{\text{avg}} \cdot \\ \cdot \text{GeneralInfo[i,4]} \cdot \text{shipping+installing} \cdot \text{c}_{\text{facade}} \cdot \text{r} \quad (4.15)$$

Same cost equations have been defined for the previously produced packs belonging to set P through variables *onhandGo[i,j]* and *shipOnHand[i]*.

4.2.4 Model Constraints

The main constraints of the model are shown in Equations 4.16-4.32. For sake of simplicity, constraints linking the decision variables to the related boolean auxiliary variables are omitted.

Production and Shipment Constraints

The first group of constraints sets due dates satisfaction and production-shipment relations. In particular, every pack i must be assembled matching its due date (Eq. 4.16) and shipped after its assembly (Eq. 4.16); every element can be assembled in one period only (Eq. 4.18) and must be produced if its due date is within the planning horizon (Eq. 4.19), which must host all of the packs produced, as declared with constraint 4.20.

$$period[i] \leq dueDate[i] \quad \forall i \in N \tag{4.16}$$

$$period[i] \leq shipment[i] \quad \forall i \in N \tag{4.17}$$

$$\sum_{j \in H} prod[i,j] \leq 1 \quad \forall i \in N \tag{4.18}$$

$$dueDate[i] \in H \Rightarrow \sum_{j \in H} prod[i,j] = 1 \quad \forall i \in N \tag{4.19}$$

$$period[i] \geq 0 \Rightarrow \text{start} \leq period[i] \leq (\text{start+horizon-1}) \quad \forall i \in N \tag{4.20}$$

Similarly, Eqs. 4.21 to 4.24 set the analogous relations for shipping, in addition Eq. 4.24 states that if a pack is produced in horizon, then it has to be shipped at the due date period. This constraint has been introduced in order to make the model consider all of the possible costs that are related to the production/shipment outputs: the benefits in anticipating the production has to be balanced with the risk of having the pack stocked for a certain period of time, so until the due date in the worst of the cases.

$$shipment[i] \leq dueDate[i] \quad \forall i \in N \tag{4.21}$$

$$\sum_{j \in H} delivery[i,j] \leq 1 \quad \forall i \in N \tag{4.22}$$

$$dueDate[i] \in H \Rightarrow \sum_{j \in H} delivery[i,j] = 1 \quad \forall i \in N \tag{4.23}$$

$$\sum_{j \in H} delivery[i,j] = 0 \ \wedge \ period[i] \geq 0 \Rightarrow shipment[i] = dueDate[i] \quad \forall i \in N \tag{4.24}$$

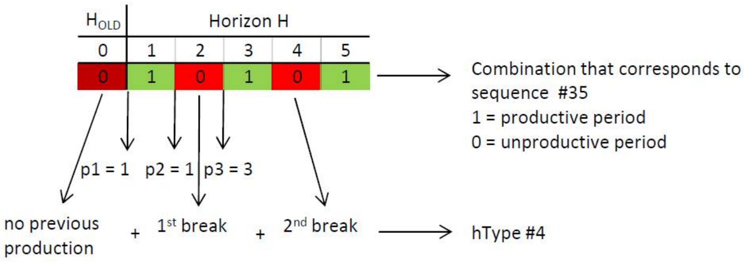
The same shipment constraints are being set for variables *shipOnhand[i]* and *onhangGo[i,j]* for packs that have already been produced in previous horizons and it is on stock at the production plant.

Learning-Forgetting and assembly line constraints

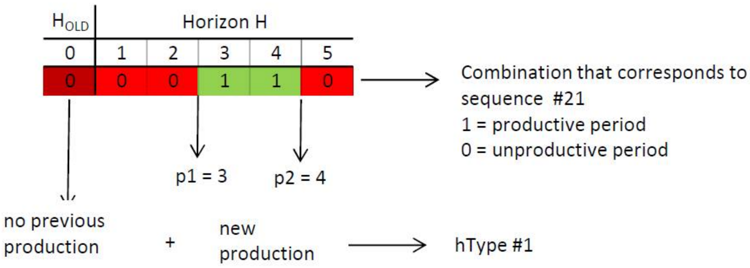
The second group of constraints (Eqs. 4.25 to 4.29) aims at calculating the total assembly time within the planning horizon, introducing lost times for setups and learning-forgetting phenomena. In particular, each part type is assigned to a defined class of setup: for exteriors and curtain walls PBEs it commonly reflects the different conveyor width needed to transfer a part along the assembly line and the time needed to adjust it, which is quite constant for every change, typically lasting half working day. Thus the different type of setups incurred within the planning horizon can be estimated by Eq. 4.25: each pack typology that appears in horizon H, is associated to its set-up through TypeInfo[k,3] parameter(column 3 of table 4.6), and hence the number of different conveyor length that occur during H is equal to the number of setups that are likely going to happen.

$$\sum_{k:TypeInfo[k,3]=u} prodType[k,j] > 0 \Rightarrow setup[u,j] = 1, \quad 0 \ \ otherwise \quad forall \quad k \in M, u \in U, j \in H \tag{4.25}$$

As concerns learning-forgetting phenomena, to exploit benefits of combinatorial optimization, each current solution in terms of quantities per part type (see Eq. 4.26) is associated with the corresponding sequence of production periods and breaks by Eqs. 4.27 - 4.29. In fact, by considering an horizon H with a certain number of periods *p*, it is possible to generate all of the possible 0-1 combinations, as explained in previous chapter at paragraph 3.5, and to associate each of them with a finitely production sequence through parameter LFsequence[s,v] (first part of Eq. 4.29). This in turn is used to assign the proper combination *s* of learning and forgetting time intervals (second part of Eq. 4.29). For example, if the horizon considered consists of 5 periods, it is possible to have $2^{p+1} = 64$ binary combinations, since each sequence has to interface with the production in previous horizon H_{old}, also; table 4.8 shows parameter LFsequence[s,v] in this case. These combinations must be associated to one of the 6 production breaks typologies *hTypes* that have been identified by applying Jaber M.Y. (1996) and that are listed in table 4.9, where an example for each type of break is shown; the connection between the two is ensured by seqPar[s,v] parameter, fully shown in table 4.10. This latter gives the model also the crucial productive and unproductive periods, which for a 5 period horizon are: *p1*, the first production period; *p2*, the starting period of the second production after the first break or first production end, according to the considered hType; *p3* is the starting period of the third (and last possible) production or the end of the second one, according to the considered hType. For example, with reference to picture 4.5a, the production combination 010101 is being associated by the model



(a) Break typology hType = 4.



(b) Break typology hType = 1.

Figure 4.5. Examples of productive and unproductive sequence and relative model parameters.

to sequence #35, thus implying p1 = start =1 (period of first production start), p2 = start =1 (period of first production end=), p3 = start + 2=3, hence identifying the break typology hType = 4. With reference to 4.5b, p1 = start+2 = 3, which is the period of the production start and p2=start+3 = 4 is the end of the batch of production, thus leading to hType = 1.

$$prodType[k,j] = \sum_{i \in N : GeneralInfo[i,2]=k} prod[i,j]\ GeneralInfo[i,4]\ \forall j \in H, k \in M \tag{4.26}$$

$$prodType[k,j] > 0 \Rightarrow prodSeq[k, j - start + 1] = 1 \quad \forall j \in H, k \in M \tag{4.27}$$

$$prodType[k,j] = 0 \Rightarrow prodSeq[k, j - start + 1] = 0 \quad \forall j \in H, k \in M \tag{4.28}$$

$$prodSeq[k,v] = LFsequence[s,v] \Rightarrow lf[k] = s \quad \forall k \in M, v \in [0..H*], s \in S \tag{4.29}$$

Table 4.8. LFsequence[s, v] parameter for a 5 period horizon H, where 1 = production in period j, 0 otherwise.

	$\mathbf{H_{old}}$	**j in H**				
Sequence	**0**	**1**	**2**	**3**	**4**	**5**
1	0	0	0	0	0	0
2	1	0	0	0	0	0
3	0	0	0	0	0	1
4	1	0	0	0	0	1
..	..	..	..	..	..	..
32	1	1	1	0	0	0
..	..	..	..	..	..	..
64	1	1	1	1	1	1

Table 4.9. Possible production breaks typologies hTypes for a 5 period horizon H, where 1 = production in period j, 0 otherwise.

		$\mathbf{H_{old}}$	**j in H**				
hType	**Description**	**0**	**1**	**2**	**3**	**4**	**5**
0	no production	0	0	0	0	0	0
1	new production with no breaks	0	1	1	0	0	0
2	production in previous horizon and 1 break in H	1	1	1	0	0	0
3	new production and 1 break in H	0	1	0	0	1	1
4	new production and 2 breaks in H	0	1	0	1	0	1
5	production in previous horizon and 1 break in H	1	1	0	0	1	1
6	production in previous horizon and 2 breaks in H	1	1	0	1	0	1

Table 4.10. seqPar[s, v] parameter for a 5 period horizon H.

Sequence	**hType**	**p1**	**p2**	**p3**
1	0	0	0	0
2	0	0	0	0
3	1	start+4	start+4	0
4	2	start+4	start+4	0
..	..	..	..	..
32	2	start	start+1	0
..	..	..	..	..
64	2	start	start+4	0

On the basis of such production periods and breaks and the current production quantities, proper preprocessed parameters for Jaber M.Y. (1996) equations in section 3.3 can be retrieved. The assignment of proper cycle times for learning-forgetting phenomena with variable quantities and periods rely on the table constraint offered by Comet. It is a kind of constraint given in extension, which bounds three variables to take values according to one of the enumerated triples contained in the table object given as its parameter. Learning and forgetting data have been organised as such tables, so that they can be easily assigned to auxiliary variables. In Eq. 4.30 is reported an example of such constraints used to assign the time interval for the first break tf1, in the case of 1 break only in the production sequence, which arises from an interruption with respect to the last production in the past, while production is considered as continuous in the current planning horizon. This variable in turn is used, together with the equivalent past production q_P and the time for the first unit T_1, to assign the time to produce the first unit t_{1P} in the current horizon (see Eq. 4.31), which is then introduced into Eq. 4.32 to assess the proper cumulative time for each part type k within the planning horizon, when learning-forgetting phenomena are considered.

$$tf1[k] = LfTf[lf[k]] \ \forall k \in M \tag{4.30}$$

$$t_{1P}[k] = LfTf[tf1[k], q_P[k], T_1[k]] \ \forall k \in M \tag{4.31}$$

$$t[k] = \frac{t_{1P}[k]}{1-l}(\sum_{j \in H} prodType[k,j])^{1-l} \ \forall k \in M \tag{4.32}$$

Stocking Area Output

As a final information, the model gives the total square meters needful to the stocking of the items, both at plant and at installation site, *areaP* and *areaS* in Eqs. 4.33 and 4.34, namely, where: C is the set of crate typologies and S is the range of the building floors; $\mathrm{crate_A}$ is the soil occupation of the crate, as per table 4.7.

$$\mathrm{areaP} = \sum_{i \in N} \sum_{c \in C} (\mathrm{shipment[i]\text{-}period[i]}) \cdot \mathrm{crate_A} \tag{4.33}$$

$$\mathrm{areaS} = \sum_{i \in N} \sum_{c \in C} \sum_{l \in L} (\mathrm{InstallDate[i]\text{-}\ shipment[i]\text{-}travel} - 3) \cdot \mathrm{crate_A} \tag{4.34}$$

In equation 4.33 packs are grouped by crate typologies, since packs can be piled one on another according to geometry analogy, while in the stock at site computation an additional sum per floor of belonging is assumed: in

Table 4.11. CP computational times.

Nb. Packs	***Nb. Types***	***Nb. panels***	*CP optimum* ***O.F. [€]***	*CP optimum* ***CPU time [h]***
10	1	10	107864	3.81
10	1	20	107033	2.36
10	1	50	105490	60.00
10	3	10	107670	108.94
10	3	20	107560	100.00
10	3	50	104786	10.14
10	5	10	107697	9.00
10	5	20	107439	101.82
10	5	50	104053	7.96
25	1	10	100798	7.15
25	1	20	99540	8.00
25	1	50	98682	9.00
25	3	10	102537	360.00
25	3	20	101042	10.01
25	3	50	97443	24.00
25	5	10	102608	10.15
25	5	20	101370	30.00
25	5	50	98160	30.00

coherence with an installation sequence that progresses level-by-level, it is important to have pack piles divided by this parameter in order to avoid extra logistics and handling.

In a tendering phase it is important to know which is the budget to allocate to the stocking area and this tool gives the chance to get a reliable number according to the best production and shipment plant. Moreover the division of the stocking area per location is useful when requesting for rental quotations.

4.2.5 Problem solving with Constraint Programming and Large Neighborhood Search

The problem has been firstly tested with the Constraint Programming (CP), through the standard COMET research algorithms, on different input data in terms of number of packs, number of family products, number of panels, to evaluate their impact on the results and CPU times.

There have been considered lists of 5, 10, 25 packs, with a total of 5, 10 or 25 panels, these latter belonging to 1, 3 or 5 family products. As a result, computational time drastically increases with the value of the three input, and becomes unsustainable when reaching 25 panels, from seconds to hours order of magnitude, up to 100-150 hours (see table 4.11). Therefore, when considering a whole project, it is unthinkable to seek mathematical optimum, since the computational time is extremely high, while it is necessary to have a tool that helps the decision-making process.

It has been then decided to hybridize the CP with the Large Neighbourhood Search, since this solving approach have been shown to perform very well in complex real life applications (see for example Meneghetti et al. (2015)), while requiring minimum adjustments of the main CP model. Once a good solution from the main CP program has been achieved, part of the variables of the solution are being freed, while the remaining ones continue to be set at the values obtained in the previous solution (see paragraph 4.1); in this way the problem can be restricted and optimized again by using the CP with a limit on the number of failures. The freed variables are approximately 20% and are random chosen among variables *period[i]*, *shipment[i]*, *shipOnHand[i]*, with i ∈ [1..N], N being the number of packs of the project. With standard LNS, the solver forces the improvement of the objective function value respect to the best solution found so far; in some cases, this implicit constraint could be too restrictive, because it could prevent the exploration of research space that could include good solutions.

COMET offers the *lnsOnFailure(nbFailures, nbStable, nbStarts)* variant, which allows the getting over of this problem: with this method a LNS iteration starts every time the number of failures reaches up to *nbFailures* value (20 in this case). A LNS restart can occur for two reasons:because the failure/time limit is reached; because the search is exhausted. A well-chosen combination of relaxation procedure and failure limit should, ideally, lead to roughly the same number of restarts caused by each of these reasons. Therefore, it is often a good idea to dynamically adapt the LNS failure or time limit, or the parameters of the relaxation procedure, based on the cause of the last restart. The method *isLastLNSRestartCompleted()* of the solver allows to test the origin of the LNS restart. It returns true in case of a complete search, and false otherwise. Statement dynamically increases the failure limit by 10%, whenever the restart is caused by a failure limit, and decreases it by 10%, whenever it is caused by a complete search Van Hentenryck and Michel (2005).

Iterations will end when the objective function results to be not improvable for *nbStable* consecutive iterations (5 in this case); at this point, a new restart will be executed, by meaning that no implicit constraint to the objective function will be applied with a potential decay with a consequent better diversification. The research is going to stop after *nbStarts* (10 in this case) restarts. Finally, the best found solution during the entire research process is being restored.

Hence, the same data input have been secondly tested with CP+LNS, which has been launched for 5 times each combination. The results are shown in tables 4.12 to 4.15 .

Graph in figures 4.6 shows a CPU increasing trend as the number of family products changes. In fact, the inserting of more than one typology in the production plan, arises the complexity of the problem, since the model has to optimize as much as possible the number of set-ups by minimizing production breaks, thus by limiting the forgetting phenomenon. For problem restricted to 5 packs, computational time grows up to about 150% (figure 4.6a); as the packs doubles to 10, time passes from 9.51 s to 5.30 min, but the order of magnitude changes from minutes to hours when having 25 packs, since time takes about 2.21 hours to give an output (figures 4.6b, and 4.6c); similar trend can be recognized in figures 4.6d and 4.6e.

Table 4.12. CP+LNS results at different values of number of packs, number of family product and number of panels.

5 packs, 1 family product, 5 panels

# Launch	Obj. Function [€]	CPU time [ms]	# best iteration
1	110680	4851	5
2	110693	3608	1
3	110680	4286	5
4	110693	3772	1
5	110680	4176	3
6	110681	3747	8
7	110680	4936	6
8	110693	3612	1
9	110693	3745	1
10	110693	3667	1

5 packs, 1 family product, 10 panels

# Launch	Obj. Function [€]	CPU time [ms]	# best iteration
1	110855	1036	1
2	110855	849	1
3	110855	865	1
4	110855	789	1
5	110855	910	1
6	110855	904	1
7	110855	846	1
8	110855	891	1
9	110855	873	1
10	110855	832	1

5 packs, 1 family product, 25 panels

# Launch	Obj. Function [€]	CPU time [ms]	# best iteration
1	109369	4525	8
2	109390	4103	10
3	109414	3997	1
4	109369	4361	6
5	109369	4214	7
6	109369	4086	9
7	109369	4801	5
8	109369	4248	7
9	109369	4463	4
10	109369	4124	4

5 packs, 3 family product, 5 panels

# Launch	Obj. Function [€]	CPU time [ms]	# best iteration
1	110637	9923	9
2	110637	9720	9
3	110670	7731	1
4	110637	12702	5
5	110637	10381	6
6	110649	8907	9
7	110670	8100	1
8	110649	9271	8
9	110637	9880	7
10	110637	9936	1

5 packs, 3 family product, 25 panels

# Launch	Obj. Function [€]	CPU time [ms]	# best iteration
1	109112	8086	9
2	109123	7078	9
3	109652	4118	1
4	109112	6837	5
5	109112	5353	6
6	109133	7979	9
7	109112	3891	1
8	109652	3589	8
9	109657	6756	7
10	109133	5595	1

5 packs, 5 family product, 10 panels

# Launch	Obj. Function [€]	CPU time [ms]	# best iteration
1	110074	5591	1
2	110074	6081	1
3	110074	6073	1
4	110074	6063	1
5	110074	5952	1
6	110074	6028	1
7	110074	6277	1
8	110074	5556	1
9	110074	5572	1
10	110074	6539	1

Table 4.13. CP+LNS results at different values of number of packs, number of family product and number of panels.

5 packs, 3 family product, 10 panels

# Launch	*Obj. Function [€]*	*CPU time [ms]*	*# best iteration*
1	110298	6130	1
2	110256	7595	3
3	110256	7025	6
4	110277	6504	3
5	110256	6746	8
6	110256	6974	6
7	110277	6603	3
8	110256	7014	6
9	110256	7071	3
10	110256	6533	6

5 packs, 5 family product, 5 panels

# Launch	*Obj. Function [€]*	*CPU time [ms]*	*# best iteration*
1	110511	5736	1
2	110511	5568	3
3	110511	5590	1
4	110511	5850	1
5	110511	6787	1
6	110511	5260	2
7	110511	5383	1
8	110511	5666	1
9	110511	6146	1
10	110511	5442	1

5 packs, 5 family product, 25 panels

# Launch	*Obj. Function [€]*	*CPU time [ms]*	*# best iteration*
1	108848	10125	1
2	108848	9172	1
3	108848	9875	1
4	108848	9641	1
5	108848	8828	3
6	108848	9407	1

10 packs, 1 family product, 10 panels

# Launch	*Obj. Function [€]*	*CPU time [ms]*	*# best iteration*
1	107295	43053	3
2	107271	35469	9
3	107899	12196	10
4	107797	21818	7
5	107867	30908	5
6	108376	23261	8
7	107817	27688	7
8	107807	39014	8
9	108366	8105	9
10	108376	12910	8

10 packs, 1 family product, 50 panels

# Launch	*Obj. Function [€]*	*CPU time [ms]*	*# best iteration*
1	106209	15762	9
2	105477	23555	10
3	105467	15255	7
4	104954	128556	6
5	105437	45047	7

10 packs, 3 family product, 20 panels

# Launch	*Obj. Function [€]*	*CPU time [ms]*	*# best iteration*
1	108042	659842	9
2	106855	421547	9
3	107557	694764	10
4	107702	324520	10
5	107681	133876	5
6	107122	86298	6
7	107858	1238403	8
8	107737	279462	9
9	107374	268000	5
10	107681	90537	10

10 packs, 5 family product, 10 panels

# Launch	*Obj. Function [€]*	*CPU time [ms]*	*# best iteration*
1	107616	85859	5
2	107725	379340	8
3	108113	85601	9
4	107699	125931	5
5	107506	379260	7
6	107526	426254	1
7	107505	315013	6
8	107638	480378	10
9	107558	30431	6
10	108092	869973	9

Table 4.14. CP+LNS results at different values of number of packs, number of family product and number of panels.

10 packs, 5 family product, 50 panels

# Launch	*Obj. Function [€]*	*CPU time [ms]*	*# best iteration*
1	103874	85859	5
2	104109	379340	8
3	103595	85601	9
4	103595	125931	5
5	103865	379260	7
6	105132	426254	1
7	103564	315013	6
8	103574	480378	10
9	104089	30431	6
10	105136	869973	9

10 packs, 1 family product, 20 panels

# Launch	*Obj. Function [€]*	*CPU time [ms]*	*# best iteration*
1	107262	36967	10
2	107241	23645	6
3	106626	54038	9
4	106622	80759	9
5	107170	95131	3
6	106633	18405	10
7	107176	38066	10
8	107800	37726	9
9	107183	24312	9
10	106622	14264	10

10 packs, 1 family product, 20 panels

# Launch	*Obj. Function [€]*	*CPU time [ms]*	*# best iteration*
1	107745	66755	10
2	107759	129890	3
3	107701	73742	10
4	107181	20144	8
5	107691	52829	8
6	107171	151597	9
7	108276	87647	10
8	107733	214276	10
9	108276	57009	9
10	107175	41463	5

10 packs, 3 family product, 50 panels

# Launch	*Obj. Function [€]*	*CPU time [ms]*	*# best iteration*
1	104982	1840751	6
2	105022	644382	7
3	104554	68328	6
4	105391	582880	10
5	104025	1083314	9
6	104584	1015635	6
7	104268	119752	9
8	104554	922567	8
9	105006	169818	7
10	105476	49388	7

10 packs, 5 family product, 20 panels

# Launch	*Obj. Function [€]*	*CPU time [ms]*	*# best iteration*
1	107354	3500088	10
2	106835	572876	10
3	107828	318931	9
4	107269	321070	10
5	107467	82953	4
6	107667	33775	5
7	107667	286330	7
8	106835	657700	8
9	107809	333881	10
10	107375	512424	8

25 packs, 1 family product, 25 panels

# Launch	*Obj. Function [€]*	*CPU time [ms]*	*# best iteration*
1	100479	318494	10
2	99936	244532	10
3	100480	64359	10
4	99936	196982	9
5	99926	277302	8
6	101606	480249	9
7	99936	255930	7
8	100469	99943	9
9	102153	264935	7
10	100469	353812	10

25 packs, 1 family product, 125 panels

# Launch	*Obj. Function [€]*	*CPU time [ms]*	*# best iteration*
1	99695	49487	9
2	99424	101669	6
3	98346	383254	6
4	99114	211753	10
5	97592	1853370	8
6	100226	97607	10
7	98034	228100	10
8	97624	493786	9
9	97676	252720	9
10	99094	50069	9

Table 4.15. CP+LNS results at different values of number of packs, number of family product and number of panels.

25 packs, 3 family product, 50 panels			
# Launch	Obj. Function [€]	CPU time [ms]	# best iteration
1	101642	798356	1
2	102250	86086	1
3	101005	205247	8
4	100318	1905956	10
5	99688	1577044	7
6	101561	1813159	3
7	100962	396699	9
8	100913	884764	1
9	102183	1843821	2
10	99900	1043615	10

25 packs, 5 family product, 25 panels			
# Launch	Obj. Function [€]	CPU time [ms]	# best iteration
1	102685	3854481	10
2	102084	20021239	6
3	101508	15756200	10
4	101507	6735520	7
5	102142	2839079	9
6	106364	4156148	10
7	103361	9309254	8
8	102189	38162563	6
9	103254	1558540	2
10	100991	12101206	10

25 packs, 5 family product, 125 panels			
# Launch	Obj. Function [€]	CPU time [ms]	# best iteration
1	98160	2930162	6

25 packs, 1 family product, 50 panels			
# Launch	Obj. Function [€]	CPU time [ms]	# best iteration
1	99325	321473	10
2	98859	404739	8
3	98577	1444846	9
4	100409	550355	6
5	98839	190433	7
6	99852	175319	9
7	100409	186098	8
8	100419	231947	10
9	99873	510403	8
10	98839	1169317	8

25 packs, 3 family product, 25 panels			
# Launch	Obj. Function [€]	CPU time [ms]	# best iteration
1	101751	486110	10
2	102293	321115	9
3	102327	1190969	9
4	103478	2256647	2
5	101213	5680221	9
6	101208	2416983	9
7	100598	1810339	10
8	106002	1242716	5
9	104783	799906	10
10	101724	5032570	8

25 packs, 3 family product, 125 panels			
# Launch	Obj. Function [€]	CPU time [ms]	# best iteration
1	96891	11474945	10
2	96204	4480397	9
3	98800	1461143	9
4	96258	2693781	2
5	97964	5668528	9
6	97945	1117573	9
7	96421	2896703	10
8	98849	5143729	5
9	97999	1901672	10
10	97096	3959357	8

25 packs, 5 family product, 50 panels			
# Launch	Obj. Function [€]	CPU time [ms]	# best iteration
1	104007	4729528	5
2	100567	5275676	9
3	100481	1523838	6
4	99939	3092660	7
5	101249	1710070	8
6	100349	7293967	7
7	101052	3542170	9
8	101091	17273893	10
9	100973	27535640	8
10	104000	7682468	10

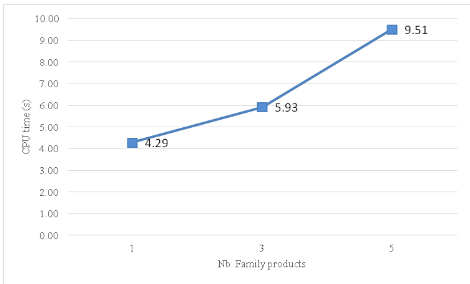
Time variations have also been analyzed in relation to the number of panels and, as can be gathered from figure 4.7, it goes up with the number of panels: with 5 packs CPU time increases by about 65.5% with squared number of panels (figure 4.7a), then it goes up to 10 minutes when packs doubles and panels increase to 50 (figure 4.7b); when taking into account 25 panels, the percentage of growing in the time is about 129% when panels quintuple; with 50 packs and 1 family product time passes from 195 s to 514 s (figure 4.7d), while with 100 packs and 3 types it increases from about 6 to 30 minutes.

A synoptic glance to the graph contained in figures 4.6 and 4.7 highlights that both the number of family types and the number of panels have a significant impact on CP+LNS computational time. Anyhow, the deepest consequence is given by the rising of the inserted number of typologies into the model, since it influence set-ups and learning-forgetting phenomena, then enhancing the complexity of the production system. In fact, as shown in figure 4.8, where CPU variation is given as typologies and number of panels are steady, the model takes much more time in production and shipment organization when the family products increase from 1 to 3, since the model has to calculate the best trade-off between learning-effect exploitation, set-up minimization and shipments fulfillments according to the crate kind; greatest examples are represented by the production of 25 and 50 packs, whose computational time gets high of approximately 598% and 1409%, figures 4.8a and b respectively.

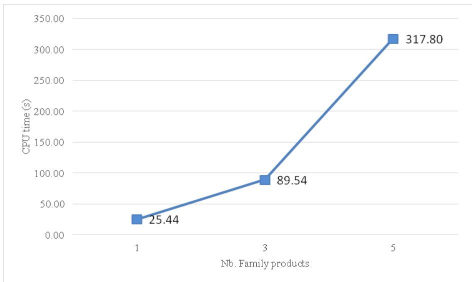
In the majority of the cases, it has been observed that the best LNS solution has been found after more than 8 iterations, as reported by graph in figure 4.9, so it has been decided to make the model run for $nbStarts$ = 10 cycles even in the case study application. This aspect is significant since if the best solution had been found on average in less than 5 iterations, then computational times would have been smaller.

Finally, comparisons between CP and LNS have been studied in order to assess the reliability of the solution offered by this latter method. Stated the complexity of the problem, it was not possible to get the optimal solution for the production system composed by more than 25 packs, since it has been tested that computational times took several days, which is not acceptable for a firm decision making tool, such the one presented in this thesis. With reference to table 4.16, in terms of objective function, even if input packs are doubled and squared, the error of the LNS remains under 1.21% and 5.76%, respectively. This result is much appreciated if computational times are taken into account, since the delta involves one or to orders or f magnitude, seconds or minutes for LNS and hours or days for the CP.

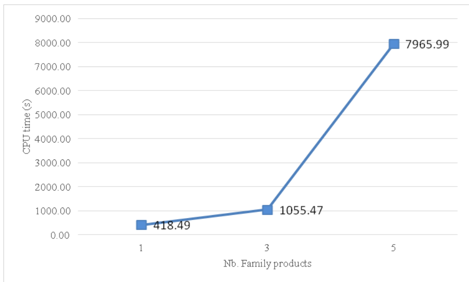
By considering the above, the final choice for the model application must fall on the LNS technique, since the computational time for the optimal solution when considering an entire project cannot be engaged with the flexibility and reactivity that a decision support tool must offer the company, hence



(a) packs = 5; panels =25



(b) packs = 10; panels =10

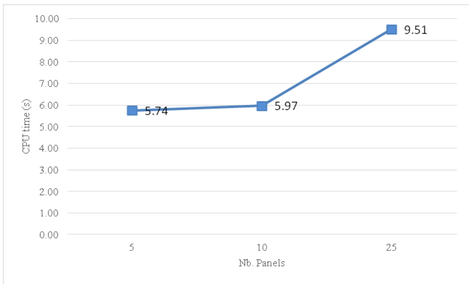


(c) packs = 25; panels =50

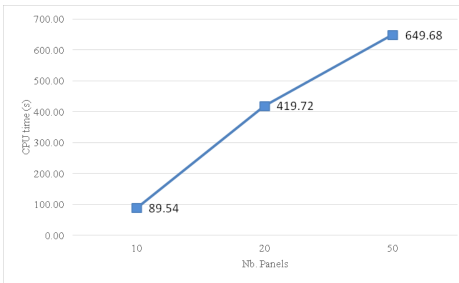
(d) packs = 50; panels =50

(e) packs = 100; panels =100

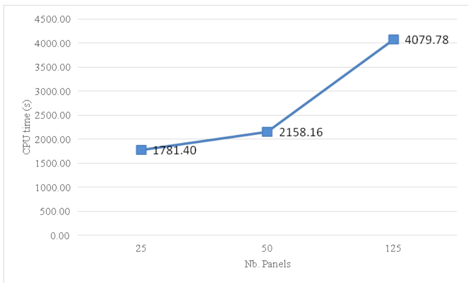
Figure 4.6. CPU times varying with the family products.



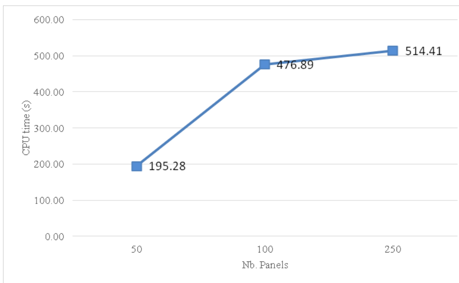
(a) packs = 5; types =5



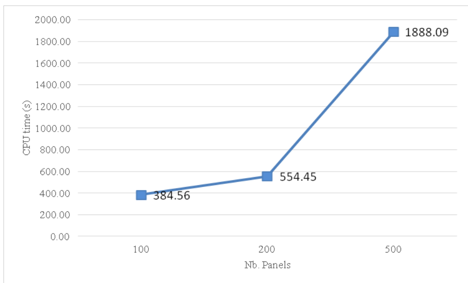
(b) packs = 10; types =3



(c) packs = 25; types =3

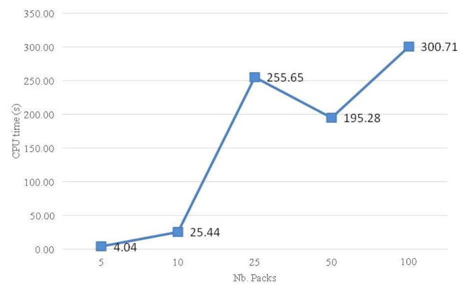


(d) packs = 50; types =1

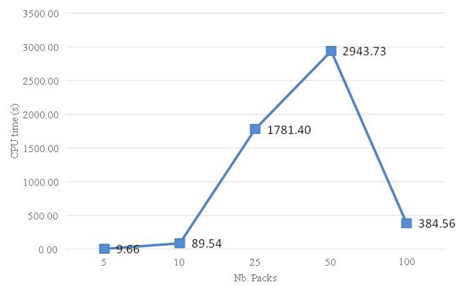


(e) packs = 100; types =3

Figure 4.7. CPU times varying with the number of panels.



(a) Nb. of family products = 1



(b) Nb. of family products = 3

Figure 4.8. CPU times varying with the number of packs.

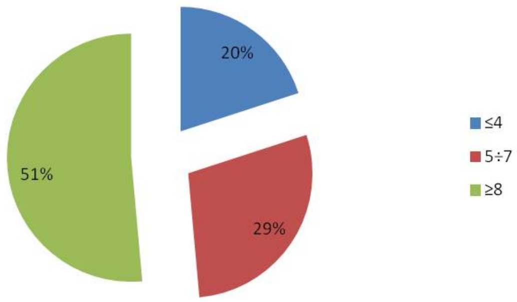


Figure 4.9. Number of iteractions for the best LNS solution.

representing a good trade-off between time spent and proposed solutions.

Table 4.16. Comparison between CP and CP+LNS results.

Nb. Packs	***Nb. Types***	***Nb. panels***	*CP optimum* ***O.F. [€]***	*CP optimum* ***CPU time [h]***	*LNS* ***O.F. avg [€]***	*LNS* ***CPU avg time [s]***	***O.F. error [%]***	***CPU time [%]***
10	1	10	107864	3.81	107887	0.03	0.02	-100
10	1	20	107033	2.36	107190	42.33	0.15	-99
10	1	50	105490	60.00	105508	45.64	0.01	-99
10	3	10	107670	108.94	108223	0.09	0.51	-100
10	3	20	107560	100.00	108178	0.42	0.57	-100
10	3	50	104786	10.14	106060	0.65	1.21	-100
10	5	10	107697	9.00	108715	0.32	0.94	-100
10	5	20	107439	101.82	108704	662.00	1.16	-99
10	5	50	104053	7.96	104702	115.70	0.62	-99
25	1	10	100798	7.15	106316	255.65	5.47	-99
25	1	20	99540	8.00	105219	0.42	5.70	-100
25	1	50	98682	9.00	104374	372.18	5.76	-98
25	3	10	102537	360.00	106523	1.78	3.88	-100
25	3	20	101042	10.01	104647	2.16	3.56	-99
25	3	50	97443	24.00	100993	4.08	3.64	-100
25	5	10	102608	10.15	106905	11449.42	4.18	-68
25	5	20	101370	30.00	106332	7.97	4.89	-99
25	5	50	98160	30.00	100676	2930.16	2.56	-97

Chapter 5

Simulations and Results

The model presented in chapter 4 has been applied to Manchester One Spinningfields building (represented in the rendering of figure 5.1), a curtain wall project awarded by Permasteelisa Group and whose learning-forgetting analysis is presented in chapter 3, paragraph 3.4.4.

The building is made of 20 floors, 2423 curtain wall panels that cover a surface of 20000 m^2.

In this chapter, results for the basic configuration for the entire project over different horizons are being detailed in paragraph 5.1, while in the following ones, simulations performed.

5.1 Resuts for the Basic Configuration

Panels have been grouped in 357 packs, according to the floor of belonging and their intrinsic geometry, as discussed in the first part of paragraph 4.2, in figure 4.3. Packs characteristics have been organized as per table 4.4, stock status is initially set to 0 for both production and shipment as per table 4.5; a total of 11 family products features have been listed into TypeInfo[k,r] (table 5.1), which is related to a CrateInfo[c,r] (table 5.2), containing 6 different typologies of crates with the suitable full-truck load information.

Learning-forgetting parameters are being set as per tables 4.8, 4.9, 4.10.

All of the input data for the entire project and for the first horizon are declined in table 5.3 and the contractual type is *job order working progress*, where weight given to the several activities, i.e. purchasing, production, shipping, installing, has been given according to the percentage of payments agreed with the client as the company progresses with the various stages of the project.

the considered contract for the choice of the objective function is *job order working progress*.

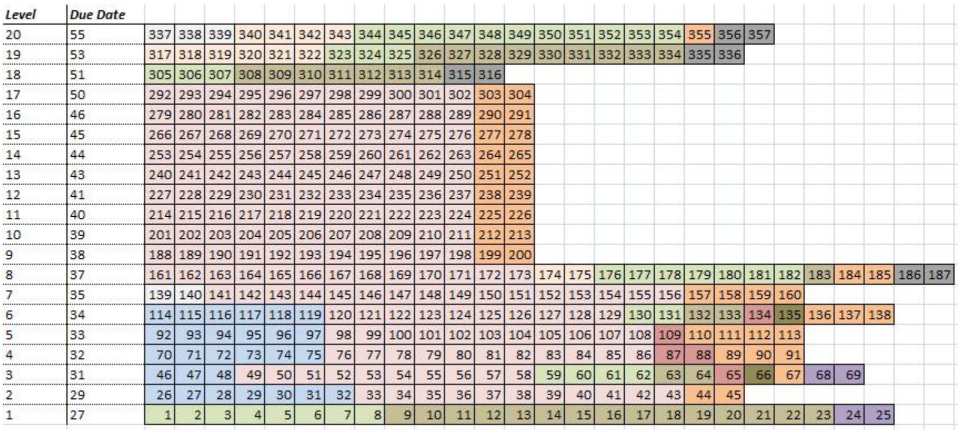
Figure 5.1. The Manchester One Spinningfields Building.

Table 5.1. TypeInfo[k,r] parameter at the start of the project, where: T_k is the estimated standard production time; Setup defines through a number that a typology implies a specific set-up to do; crate type points out the category of pallet; Q_{std} is the foreseen quantity of panels that have to be produced to reach T_k; P_{last} is the last period in which family k has been produced; α indicates the level of experience remembered

Family product k	$\bar{T}_k$ **[min]**	**Setup class**	**Crate type**	Q_{std} **[units]**	P_{last}	α **[units]**
1	294	1	1	480	0	0
2	294	1	1	480	0	0
3	294	1	1	480	0	0
4	426	1	2	375	0	0
5	426	1	2	375	0	0
6	426	1	2	375	0	0
7	684	2	3	250	0	0
8	570	2	4	110	0	0
9	684	3	5	250	0	0
10	570	3	5	110	0	0
11	570	4	6	110	0	0

Table 5.2. CrateInfo[c,r] parameter for the studied project, where: $crate_H$ is the number of crates of typology that can be stacked onto each other; $crate_P$ is the number of columns of piled packs that can be loaded in the mean of transport; $crate_W$ is the number of packs that can be stacked in the warehouse; $crate_A$ is the area occupied by the pack.

crate c	**$crate_H$**	**$crate_P$**	**$crate_W$**	**$crate_A$ [m^2]**
1	1	3	2	9
2	1	2	2	9
3	2	3	4	3
4	2	3	4	4
5	1	3	2	9
6	2	2	4	9



Level	Due Date																											
20	55	337	338	339	340	341	342	343	344	345	346	347	348	349	350	351	352	353	354	355	356	357						
19	53	317	318	319	320	321	322	323	324	325	326	327	328	329	330	331	332	333	334	335	336							
18	51	305	306	307	308	309	310	311	312	313	314	315	316															
17	50	292	293	294	295	296	297	298	299	300	301	302	303	304														
16	46	279	280	281	282	283	284	285	286	287	288	289	290	291														
15	45	266	267	268	269	270	271	272	273	274	275	276	277	278														
14	44	253	254	255	256	257	258	259	260	261	262	263	264	265														
13	43	240	241	242	243	244	245	246	247	248	249	250	251	252														
12	41	227	228	229	230	231	232	233	234	235	236	237	238	239														
11	40	214	215	216	217	218	219	220	221	222	223	224	225	226														
10	39	201	202	203	204	205	206	207	208	209	210	211	212	213														
9	38	188	189	190	191	192	193	194	195	196	197	198	199	200														
8	37	161	162	163	164	165	166	167	168	169	170	171	172	173	174	175	176	177	178	179	180	181	182	183	184	185	186	187
7	35	139	140	141	142	143	144	145	146	147	148	149	150	151	152	153	154	155	156	157	158	159	160					
6	34	114	115	116	117	118	119	120	121	122	123	124	125	126	127	128	129	130	131	132	133	134	135	136	137	138		
5	33	92	93	94	95	96	97	98	99	100	101	102	103	104	105	106	107	108	109	110	111	112	113					
4	32	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91					
3	31	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69			
2	29	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45							
1	27	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25		

Figure 5.2. Schematic representation of Manchester One Spinningfields Building facade.

A schematic representation of the building facade is available in figure 5.2, where each cell represents one pack with its unique reference code; each pack is coloured according to its family product and on the left column, floors and due dates are specified.

5.1.1 First horizon results

With reference to the nomenclature presented in chapter 4, the objective function worth for the first 5 weeks of planning is 26712.7 €, split into:

- *unproduction*: $c_{up} \sum_{j=1}^{5} unprod[j] = 0.0$ €;
- *set-ups*: $c_{su} \sum_{j=1}^{5} sumSu[j] = 11980.0$€;

Table 5.3. Basic configuration input data.

Group	Input	Range	Description	Value
1	nTypes		No. of typologies of the project	11
1	panels		No. of panels of the project	2423
1	nPacks		No. of packs of the project	357
1	nSetup		No. of possible setups in the project	4
1	startLev		First level of the building	1
1	endLev		Last level of the building	20
2	start		Start period of the planning horizon	24
2	horizon		No. of periods in planning horizon	5
3	travel		Transport lead time [periods]	1
4	capacity		Assembly line capacity over planning horizon[minutes]	23040
4	maxOver		Allowed production overcapacity [%]	20
4	timeSu		Cumulated time for set-up [minutes]	3120
5	volume		Loading volume of the mean of transport [m^3]	92
6	l		learning constant of family products	0.376
6	tB		total forgetting time of family products [periods]	5
6	std		average multiplying factor for first unit production time	3
7	c_{up}		Cost for production loss [€/min]	0.64
7	c_{su}		Cost for line setup [€/min]	0.96
7	c_{ltl}		Cost for less than truck loading [€/m^3]	52.5
7	c_{over}		Extra cost for overtime [€/min]	0.32
7	c_{facade}		Sell price for the complete facade [€/m^2]	600
7	r_b		interest rate for bank capital assets [%]	5
7	r_h		risk rate for extra handling over time [%]	3
7	r_d		risk rate for material damage over time [%]	2
8	purchasing		weight of purchasing activity [%]	54
8	production		weight of production activity [%]	8
8	shipping		weight of shipping activity [%]	2
8	installing		weight of installing activity [%]	22
8	sqm_{avg}		average square meters per panel [m^2]	8.1
8	t_{avg}		average tender production time per panel [minutes]	356.7

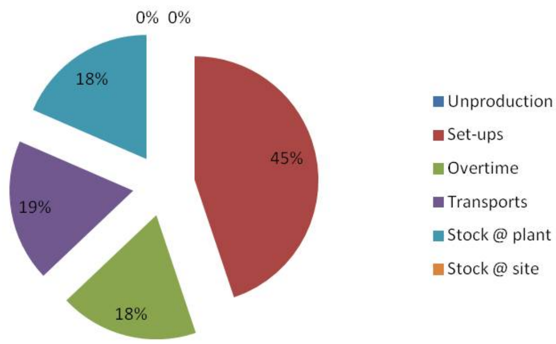


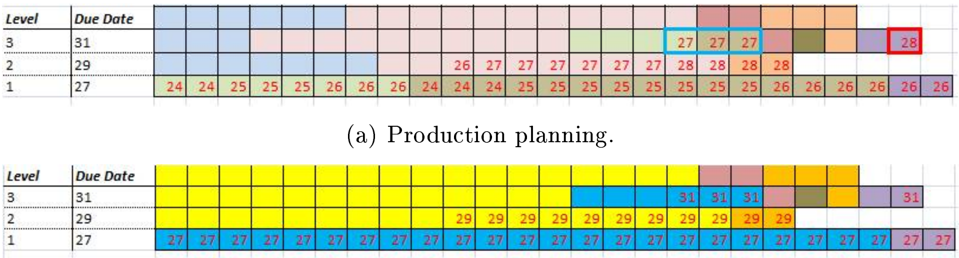
Figure 5.3. Total cost split for basic result, first horizon.

- *overtime*: $c_{over} \sum_{j=1}^{5} overtime[j] = 4964.2$ €;
- *less-than-truck load*: $c_{ltl} \sum_{j=1}^{5} unload[j] = 4830.00$ €;
- *capital costs*: $C_{capital} = 4937.76$ €;

As shown in picture 5.3, the major cost item is due to set-ups (45%), followed by less-than-truck load transports (19%), overtime (18%), and finally capital costs (18%). It comes as an evidence that with this plan there is no idle time of the assembly line, since the activities related to production (production + purchasing) represent the 62% of the facade cost, as per table 5.3), therefore the model suggest to apply overtime. In fact, the cost related to the unproduction takes into account not only the idle time of the assembly line, but also in terms of capitalization, since it prevents the company for being paid for the production of the units that could have been assembled if the operators would not have stopped (see Eq. 4.9).

Unproduction and Overtime Costs

The *production plan* proposed is given in figure 5.4a, where the packs are represented by cells coloured as per product family; the number inside each cell or pack is the production week suggested by the model. The total packs to produce are 40 and at first sight it is possible to appreciate that all of the panels that have the due date in horizon are being produced and that the plans suggests a certain anticipation of packs belonging to defined family products. In fact, there are several packs belonging to levels 2 and 3 whose due date is out of the considered planning horizon, which involves periods 24-28:



(a) Production planning.

(b) Shipment planning.

Figure 5.4. Production and Shipment plannings for first horizon.

- 2 brown packs and 1 green pack of level 3 (blue squared) have been anticipated in order to exploit learning effect of the same typology being produced in periods 24, 25, 26 for level 1;
- 1 purple pack of level 3 (red squared) has been anticipated in order to limit the forgetting phenomenon of the same typology being produced in period 26 for level 1, but also to saturate as much as possible the capacity of the assembly line in week 28, since this product type requires more time to be produced than the others considered in this planning horizon (+33.8%);
- 11 packs of level 2 of other 2 different families have been anticipated in order to fulfill the capacity of the assembly line;

The pattern of the model is to minimize as much as possible the unproduction of the assembly line, which is evident in the case of the level 2 anticipation: the model prefers to saturate the line and go for overtime rather than paying for the assembly line. Moreover, level two is chosen instead of level 3 because it is more convenient and less risky than having the material immobilized on stock.

Total production time per period in terms of minutes is available in the histogram of figure 5.5, where the blue bar is the time worked out on the assembly line, the red one is the time spent on set-up arranging, the orange line shows the available capacity on the line that corresponds to 12 workers, which is the minimum capacity of the assembly line for Permasteelisa Group. Therefore the part of the bars which exceed the red line represent the necessary overtime. During periods 24 and 25, the line is fully involved in the fabrication of the first floor panels which have the due date in horizon, and overflow of production time is required, 3.7% and 9.9% namely. The peak is reached in week 26, when the the planning has to face 2 set-ups: required capacity is 30053 min against an availability of 23040 min, that means that an overtime is needed for 7013 min, which corresponds to have approximately 3 more people on the assembly line. This is a bearable additional work-force

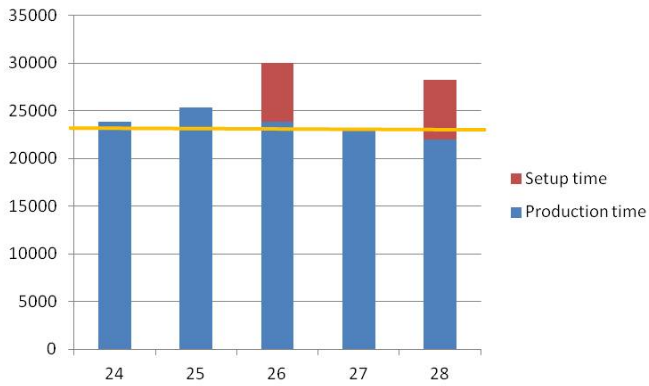


Figure 5.5. Capacity plan for the first horizon [minutes].

for these kind of productions, since the product to be assembled is so huge (typical dimensions of curtain wall panels are approximately 1500x3500 mm) that there is enough space on the line to face these situations. Another overflow, happens in week 28 when 5210 min are necessary to face set-ups and to exploit the benefits of learning effect for the anticipated panels of level 3.

By knowing the resource planning in advance, the firm can foresee how many working hours are needed on the assembly line throughout the entire production process and therefore to manage the work force at the best.

Set-ups Costs

The impact of this production plan on the set-ups, which in a curtain wall production can last half working date, is given in picture 5.6, where the cells/packs have been coloured according to the kind family, and inside each pack the implied set-up class is reported. The red line reveals that an enlargement of the assembly line is going to happen: in the first 2 periods there are no set-ups, while there will be 2 of them in week 26 and other 2 in week 28. Since the first level is formed by family products that belong to two different setup-classes, the first two set-ups are unavoidable to meet the due dates. The model suggests to operate an additional set-up with the assembly of the purple unit, which has been chosen in order to minimize the forgetting phenomenon over periods and to limit the stocking at plant that would have happened if the pack had been produced with the same typology packs of level one. Moreover, the model places this pack at the end of period 28, so the adjacent purple pack is going to be the first in period 29, in the perspective of set-up optimization seeking.

Set-up significance is appreciable also in histogram 5.5, since for example in weeks 26 and 28, the enlargement of the line is causing capacity overflow turning into overtime requests.

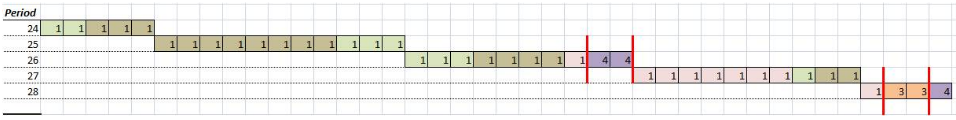


Figure 5.6. Production plan per set-up.

Less-than-truck Load Costs

Shipment plan is offered in figure 5.4b, where different colour corresponds to different crate typology and so to new trucks also, since means of transports are fulfilled with panels belonging to the same crate family. The choice of having packs belonging to the same crate typology in the same truck, is the concretization of the firm's common practice, since during the tender phase, to whom this model is addressed to, it is not possible to know the exact schedule of the production assembly line, hence it is not possible to know which is the exact sequence of the packs coming out of the line and consequently which is the exact fulfillment of the trucks. In this phase, dimensions and number of packs are reliable but indicative, so that this assumption is being made in order to consider a certain safety margin on transports calculation.

Actually, packs that are going to be effectively shipped, are the ones belonging to the first level, which is the only one whose due date falls into the planning horizon. In fact, as per constraint given in equation 4.24, the packs that have due date outside the horizon and whose production is anticipated must be assigned a shipment date that overlaps the due date. This choice has been made in order to make the model consider all of the possible costs that are related to the production/shipment outputs: the benefits in anticipating the production has to be balanced with the risk of having the pack stocked for a certain period of time, so until the due date in the worst of the cases. These out-of-horizon anticipated packs, are going to be the on-hand packs of the next horizon. For these reasons, their stock immobilization is taken into account in the capital cost for unshipment, but the costs associated to the unload, which is an amount of 4830.00 €, are related only by the less-than-truck load of period 27. This latter expense, is due to the fact that for first level there are two groups of mean on transports that, if summarized, are generating one full-truck loss:

- family #3 first level ones (blue packs in picture 5.4b): a truck is fulfilled with 2 packs of this type (by referring to table 5.2, $crate_H \cdot crate_P = 1 \cdot 2 = 2$), so, since there are 23 packs to be shipped, 11 of them are going to be full and 1 one them is going to be half empty;

- family #6 first level ones (violet packs in picture 5.4b): a truck is fulfilled with 4 packs of this type (by referring to table 5.2, $crate_H \cdot$

$crate_P = 2 \cdot 2 = 4$), so, since there are 2 packs to be shipped, just 1 half-truck is needed;

Shipment date, which is reported inside each cell, coincide with the pack due date: the model suggests to minimize the stock at site in favour of stock at plant rather than maximizing the truck loading. This is explainable by the fact that the impact weight set by the user according to the type of contract with the client, is much higher for the uninstalling than for the unshipment of the packs, namely 22% and 2% (as per table 5.3).

Capitalization costs

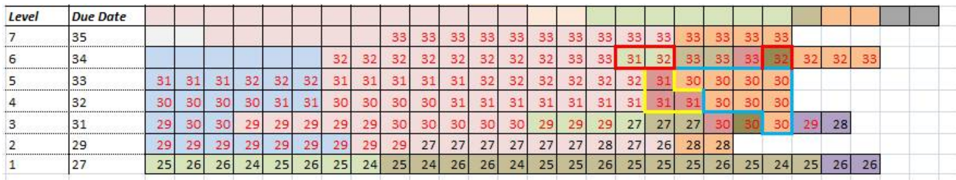
The capitalization costs are the sum of the costs for unproduction, costs for unshipping and costs for uninstalling, that amount to 4937.8 €and overlaps with the solely unshipping ones. These costs are hidden costs that are frequently underestimated by the firm that, by the way, represent the 18% of the total costs in this case.

The cost linked to the idle time of the assembly line ($\text{cap}_{\text{unprod}}$), gives the impact of the loss of productivity during the idle period in terms of payment postponement by the client, since the firm is paid for the purchasing and production activity percentages of the cost facade as the production of the packs can be invoiced. In this horizon, among the weights of the activities that deal with the different capital costs, the one related to unproduction (see Eq.4.9) is the heaviest one (purchasing+production = 62%), therefore the model seeks the maximum optimization of it and in this case it is even zero.

The part of the capital cost due the stock on site, which weights the 22% of the total facade costs according to the impact of the installation process (Eq. 4.11), is reduced to zero: the stock at plant is preferred by the model, because the activity related to it (shipping) is worth 8% of the facade cost (refer to Eq. 4.10). Therefore, just in time shipments are being suggested.

The stock at the plant prevents the company from the income resulting from the pack shipping activity for all of the stocking period. By following similar reasonings done for the unproduction capital cost, and by applying equation 4.10 the total cost of 4937.8 is reached, which corresponds to packs being stocked at site for an equivalent of 81 periods.

Finally, the model gives the output of the suitable storage area that should be held in order to respect the production planning proposed, as per Eqs. 4.33-4.34. In this case, the only area that is needed is at the production plant and equals 378.25 m^2. This information is really useful for the firm, since in a preliminary phase a budget for the stocking area has to be set, therefore the tender department can use the output of the model to define the correct associated costs.



(a) Production planning.

(b) Shipment planning.

Figure 5.7. Production and shipment plannings for horizon #2.

Results overview for the next horizons

As for horizon #2 (periods 29-33), with reference to picture 5.7a there have been proposed:

- the blue squared items in period 30;
- yellow squared production anticipations, in week 31;
- packs highlighted in red have been anticipated in order to limit the forgetting phenomenon, since the last period of production has been 29 for the green family and 30 for the brown one;

where packs with week written in red are the ones involved and the packs in black are the ones produced/shipped in the previous horizon.

On the shipment side, by having a look at picture 5.7b, a shipment grouping has been done with the red squared elements, which, all together, can fill up a truck for $2/3 = 66\%$.

Production and shipment proposals for horizon #3 (periods 34-38), involving weeks 34 to 38, are offered in picture 5.8. Anticipation deals with yellow square: the program seeks set-up minimization of family number 9. Shipment plan shows that 6 violet underlined packs have been shipped all together, thus maximizing truck fulfillment, which is reached with 6 units exactly.

Horizon #4 (weeks 39-43) is planned as per figure 5.9. As for the production plan, panels highlighted with yellow and blue squares have been anticipated for set-up seeking. Several shipment groupings have been performed, as underlined in purple, green, light blue, blue and red squares.

Level	Due Date																											
10	38	38	38	38	38	38	38	38	38	38	38	38	38	38
9	37	37	37	37	37	37	37	37	37	37	37	37	36	36
8	36	36	36	36	36	36	36	36	36	36	36	36	36	36	36	36	35	35	35	35	35	35	35	35	36	36	35	33
7	35	34	34	34	34	34	34	34	35	33	33	33	33	33	33	33	33	33	33	33	33	33	33
6	34	34	34	34	34	34	34	32	32	32	32	32	32	32	32	33	33	31	32	33	33	33	32	32	32	33
5	33	31	31	31	32	32	32	31	31	31	31	31	32	32	32	32	32	32	31	30	30	30	30
4	32	30	30	30	30	31	31	30	30	30	30	31	31	31	31	31	31	31	31	31	30	30	30
3	31	29	30	30	29	29	29	29	29	30	30	30	30	30	29	29	29	27	27	27	30	30	30	29	28
2	29	29	29	29	29	29	29	29	29	29	27	27	27	27	27	27	28	27	26	28	28
1	27	25	26	26	24	25	26	25	24	25	24	26	26	24	25	25	26	25	25	25	26	25	24	25	26	26

(a) Production planning.

Level	Due Date																											
10	38	38	38	38	38	38	38	38	38	38	38	38	38	38
9	37	37	37	37	37	37	37	37	37	37	37	37	36	36
8	36	36	36	36	36	36	36	36	36	36	36	36	36	36	36	36	36	36	36	36	36	36	36	36	36	36	36	36
7	35	35	35	35	35	35	35	35	35	35	35	35	35	35	35	35	35	35	35	35	35	35	35
6	34	34	34	34	34	34	34	34	34	34	34	34	34	34	34	34	34	34	34	34	34	34	34	34	34	34
5	33	33	33	33	33	33	33	33	33	33	33	33	33	33	33	33	33	33	31	33	33	33	33
4	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	31	31	32	32	32
3	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31
2	29	29	29	29	29	29	29	29	29	29	29	29	29	29	29	29	29	29	29	29	29
1	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27

(b) Shipment planning.

Figure 5.8. Production and shipment plannings for horizon #3.

Level	Due Date																											
16	44	42	42	42	42	43	43	43	43	43	43	43
15	43	41	41	41	41	41	41	42	42	42	42	42	40	40
14	42	40	40	40	40	40	40	40	40	41	41	41	40	40
13	41	39	39	39	39	39	39	39	39	40	40	40	39	39
12	40	39	39	39	39	39	39	39	39	39	39	39	39	39
11	39	39	39	39	39	39	39	39	39	39	39	39	39	39
10	38	38	38	38	38	38	38	38	38	38	38	38	38	38
9	37	37	37	37	37	37	37	37	37	37	37	37	36	36
8	36	36	36	36	36	36	36	36	36	36	36	36	36	36	36	36	35	35	35	35	35	35	35	35	36	36	35	33
7	35	34	34	34	34	34	34	34	35	33	33	33	33	33	33	33	33	33	33	33	33	33	33
6	34	34	34	34	34	34	34	32	32	32	32	32	32	32	32	33	33	31	32	33	33	33	32	32	32	33
5	33	31	31	31	32	32	32	31	31	31	31	31	32	32	32	32	32	32	31	30	30	30	30
4	32	30	30	30	30	31	31	30	30	30	30	31	31	31	31	31	31	31	31	31	30	30	30
3	31	29	30	30	29	29	29	29	29	30	30	30	30	30	29	29	29	27	27	27	30	30	30	29	28
2	29	29	29	29	29	29	29	29	29	29	27	27	27	27	27	27	28	27	26	28	28
1	27	25	26	26	24	25	26	25	24	25	24	26	26	24	25	25	26	25	25	25	26	25	24	25	26	26

(a) Production planning.

Level	Due Date																											
15	43	42	43	43	43	43	43	43	43	43	43	43
14	42	42	42	42	42	42	42	42	42	42	42	42	42	42
13	41	41	41	41	41	41	41	41	41	41	40	40	40	40
12	40	40	40	40	40	40	40	40	40	40	40	39	39	40
11	39	39	39	39	39	39	39	39	39	39	39	39	39	39
10	38	38	38	38	38	38	38	38	38	38	38	38	38	38
9	37	37	37	37	37	37	37	37	37	37	37	37	36	36
8	36	36	36	36	36	36	36	36	36	36	36	36	36	36	36	36	36	36	36	36	36	36	36	36	36	36	36	36
7	35	35	35	35	35	35	35	35	35	35	35	35	35	35	35	35	35	35	35	35	35	35	35
6	34	34	34	34	34	34	34	34	34	34	34	34	34	34	34	34	34	34	34	34	34	34	34	34	34	34
5	33	33	33	33	33	33	33	33	33	33	33	33	33	33	33	33	33	33	31	33	33	33	33
4	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	31	31	32	32	32
3	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31
2	29	29	29	29	29	29	29	29	29	29	29	29	29	29	29	29	29	29	29	29	29
1	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27

(b) Shipment planning.

Figure 5.9. Production and shipment plannings for horizon #4.

Level	Due Date																											
20	48	47	47	47	46	46	46	47	46	46	46	46	47	47	47	47	47	48	48	46	46	46						
19	47	45	45	45	45	45	46	45	45	45	45	45	45	45	45	46	46	46	46	45	46							
18	46	44	44	45	44	45	44	44	45	45	44	44	44															
17	45	44	44	44	44	44	44	44	44	44	44	44	44	44														
16	44	42	42	42	42	43	43	43	43	43	43	43	44	44														
15	43	41	41	41	41	41	41	42	42	42	42	42	40	40														
14	42	40	40	40	40	40	40	40	40	41	41	41	40	40														
13	41	39	39	39	39	39	39	39	39	40	40	40	39	39														
12	40	39	39	39	39	39	39	39	39	39	39	39	39	39														
11	39	39	39	39	39	39	39	39	39	39	39	39	39	39														
10	38	38	38	38	38	38	38	38	38	38	38	38	38	38														
9	37	37	37	37	37	37	37	37	37	37	37	37	36	36														
8	36	36	36	36	36	36	36	36	36	36	36	36	36	36	36	36	35	35	35	35	35	35	35	35	36	36	35	33
7	35	34	34	34	34	34	34	34	35	33	33	33	33	33	33	33	33	33	33	33	33	33	33					
6	34	34	34	34	34	34	34	32	32	32	32	32	32	32	32	33	33	31	32	33	33	33	32	32	32	33		
5	33	31	31	31	32	32	32	31	31	31	31	31	32	32	32	32	32	32	31	30	30	30	30					
4	32	30	30	30	30	31	31	30	30	30	30	31	31	31	31	31	31	31	31	31	30	30	30					
3	31	29	30	30	29	29	29	29	29	30	30	30	30	30	29	29	29	27	27	27	30	30	30	29	28			
2	29	29	29	29	29	29	29	29	29	29	27	27	27	27	27	27	28	27	26	28	28							
1	27	25	26	26	24	25	26	25	24	25	24	26	26	24	25	25	26	25	25	25	26	25	24	25	26	26		

(a) Production planning.

Level	Due Date																											
20	48	47	47	47	46	46	46	47	46	46	46	46	47	47	47	47	47	48	48	46	46	46						
19	47	45	45	45	45	45	46	45	45	45	45	45	45	45	45	46	46	46	46	45	46							
18	46	44	44	45	44	44	44	44	45	45	45	44	44															
17	45	44	44	44	44	44	44	44	44	44	44	44	44	44														
16	44	42	42	42	42	43	43	43	43	43	43	43	44	44														
15	43	41	41	41	41	41	41	42	42	42	42	42	40	40														
14	42	40	40	40	40	40	40	40	40	41	41	41	40	40														
13	41	39	39	39	39	39	39	39	39	40	40	40	39	39														
12	40	39	39	39	39	39	39	39	39	39	39	39	39	39														
11	39	39	39	39	39	39	39	39	39	39	39	39	39	39														
10	38	38	38	38	38	38	38	38	38	38	38	38	38	38														
9	37	37	37	37	37	37	37	37	37	37	37	37	36	36														
8	36	36	36	36	36	36	36	36	36	36	36	36	36	36	36	36	35	35	35	35	35	35	35	35	36	36	35	33
7	35	34	34	34	34	34	34	34	35	33	33	33	33	33	33	33	33	33	33	33	33	33	33					
6	34	34	34	34	34	34	34	32	32	32	32	32	32	32	32	33	33	31	32	33	33	33	32	32	32	33		
5	33	31	31	31	32	32	32	31	31	31	31	31	32	32	32	32	32	32	31	30	30	30	30					
4	32	30	30	30	30	31	31	30	30	30	30	31	31	31	31	31	31	31	31	31	30	30	30					
3	31	29	30	30	29	29	29	29	29	30	30	30	30	30	29	29	29	27	27	27	30	30	30	29	28			
2	29	29	29	29	29	29	29	29	29	29	27	27	27	27	27	27	28	27	26	28	28							
1	27	25	26	26	24	25	26	25	24	25	24	26	26	24	25	25	26	25	25	25	26	25	24	25	26	26		

(b) Shipment planning.

Figure 5.10. Production and shipment plannings for horizon #5.

Production plans for horizon #5 (weeks 44-48) asks for the anticipation in yellow, blue, red; shipment plan minimizes the waste of space in trucks with blue and green highlighted elements.

Objective functions for horizons 1 to 5 are available in table 5.4 and their percentage composition in figure 5.11.

Unproduction costs are zero or negligible for horizons 1-4, while it is the greatest part of horizon 5. This phenomenon is due to the fact that the necessary capacity to produce the upper levels within the due date is less than the minimum, which is 12 people on assembly line. Visual impact of this aspect is given in figure 5.12, where it can be seen that the total minutes spent by the assembly line (productive time + set-up) is much smaller than the unproductive one. By knowing this information in advance, the production manager can plan a recovery activity for the workers, i.e. spending the

Table 5.4. Total costs per horizon [€].

	1	**2**	**3**	**4**	**5|Total**	
Unproduction	0.00	1703.68	1496.12	113.03	36434.44	39746.83
Set-ups	11980.80	49996.00	3456.00	3456 .00	14976.00	83864.80
Overtime	4964.16	2576.98	10873.54	1297.46	0.00	19712.14
Transports	4830.00	20930.00	19320.00	6440.00	20125.00	71645.00
Stock @ plant	4937.76	10439.28	1108.00	6531.84	4918.32	27935.20
Stock @ site	0	855.36	427.68	4276.80	1283.04	6842.88
Total	26712.72	86502.10	36681.42	22115.13	78371.55	250382.92

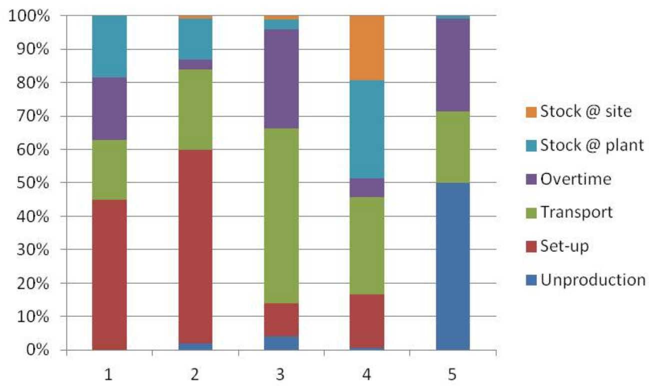


Figure 5.11. Total costs partition per horizon [%].

resources into other factory activities (cleaning, warehousing, working into other projects, development programs). In the light of this, the model offers the possibility to draw the resource capacity plan for the project, which is offered in histogram in picture 5.13, where the blue part is the planned capacity necessary to assemble the panels, the yellow part is the extra-time (extra hours to assemble the pieces + set-ups) and the red line represents the minimum assembly line capacity. As an evidence, during the first horizon, minimum capacity is enough, while in the second one it has to be increased of the 100% (from 12 to 24 workers) in order to find out a feasible solution. This is possible because with such a huge product, the assembly operations are long enough to allow the capacity to be increased and even doubled, if necessary, through the activation of a second assembly line or a second shift. In these kind of productions, when these measures are adopted, the over-capacity must be maintained for quite a long time (typically 4/5 weeks) because of hiring on demand contracts duration, that is why the model has been set for having a constant capacity over the horizon. 3^{rd} and 4^{th} horizons require not so much more than the minimum (14 people); in the last horizon, instead, the minimum capacity is even overflowing.

The resource plan in terms of stocking areas required are visible in table

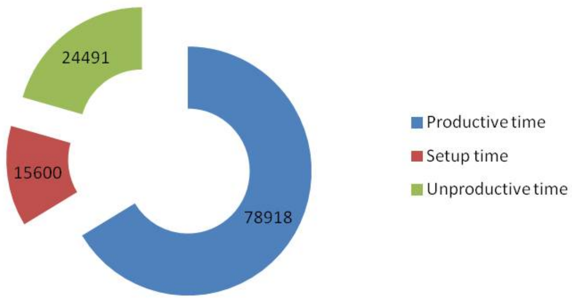


Figure 5.12. Total costs per horizon [%].

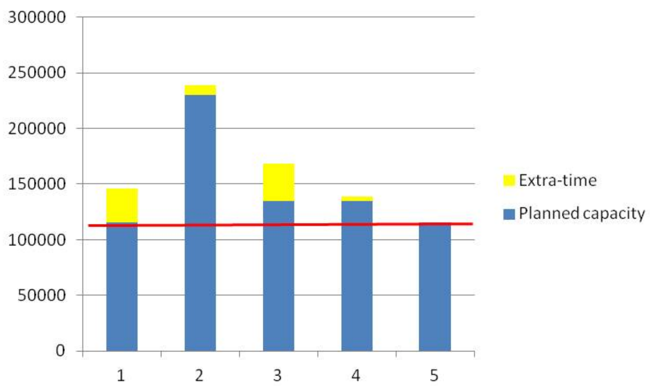


Figure 5.13. Project capacity plan [minutes].

Table 5.5. Stocking area plan per horizon [m^2].

	1	**2**	**3**	**4**	**5**
Area @ plant	378.25	717.25	128.50	443.50	416.50
Area @ site	-	6.00	8.00	48.00	52.00

5.5. The solution found lead to a in-house stocking strategy throughout all of the horizons, since, as per equations 4.10 and 4.11, the project loses more money due to the uninstalling, which weights 22%, rather than with the unshipping.

5.2 Changing Contract Type

Contract type B, *payment at work completion*, is set in this simulation in order to find out which is the difference in costs between the two contractual agreements. This simulation is very important to the company in a preliminary phase, where the contractual agreement with the client has still to be fixed. In fact, the stakeholders can understand which are the impacts on the economic side of the project when the client suggests a certain type of contract. In this case a difference is the activities impacting on capital costs, as explained in previous chapter paragraph, 4.2.3, and summarized in the following table:

Table 5.6. Activities impacting on capital costs per contract type.

	Contract A	*weight [%]*	*Contract B*	*weight [%]*
cap_{unprod}	purchasing+production	62	purchasing	54
cap_{unship}	shipping	2	production	8
$cap_{uninstall}$	install	22	install+shipping	24

Moreover, an additional risk rate $r_f = 2\%$ is added to total rate r, in order to take into accont the financial exposure that the firm has to face with this contract.

Comparison between the two types of contract is offered in picture 5.14. The total cost is of 36544.08 €, which is 36.8% higher than the contract type A, by meaning that the company may loose an equivalent gain by signing contract B. In this configuration, stock at plant represents the major deviation, because, even if the actual stocking periods are less than the ones in contract A (62 and 81 respectively), there is an increasing weight of the unshipment capital cost, that passes from the 2% to the 8%.

In this case the model is a decision support tool in giving the company the chance to understand which is the best contractual agreement to be sought with the client according to the payment method and to the weight assigned

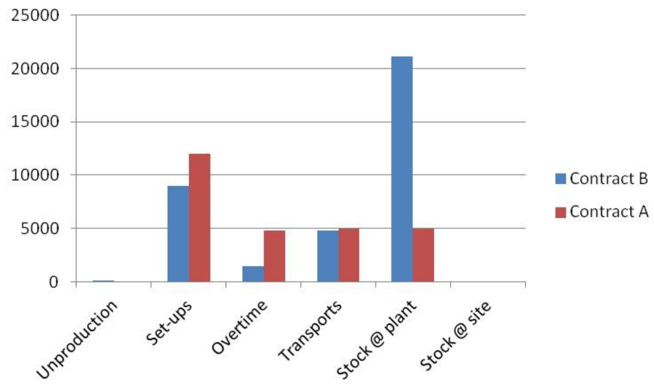


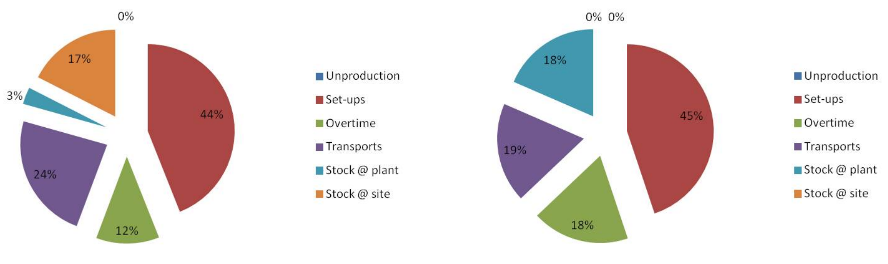
Figure 5.14. Comparisons costs between the two contract typologies.

to each phase of the project. Therefore it is fundamental to know which is the financial impact of signing one kind of agreement instead of another one, in order to propose the client the most convenient. On the other hand, if the best case makes not the deal, the company has the chance to know in advance how much is the financial damage in order to take the corrective actions accordingly.

5.3 Scope Of Work Adaptation

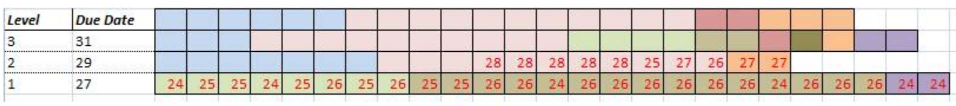
The scope of this simulation is to state which is the model behaviour when changing the weight of the activities. This can be useful since there are projects in which, for example, the installation phase is not in the scope or work of the contract or it represents a minimum. In this latter case the weight of the shipment is 22% and installation activity is reduced to 2% because the installation phase is not in the contractual agreement with the client.

Costs are split as per figure 5.15a: the main part of the costs remains the set-up one, while stocks at plant and at site growths are noteworthy. In fact the stock at site is 17% here, because the asset immobilization there is the 18% cheaper than the basic configuration. For this reason this stock at site formula is preferred. This is confirmed by the fact that almost all of the shipments are just-in-time, as shown in picture 5.16b and that production anticipations are reduced, as per 5.16a. The increasing of the inventory at plant respect to the basic configuration (23% to 3%) is due to the increasing of the 20% of the shipment activity and its trade-off with the less-than-truck load costs, whose impact is greater of 2%.

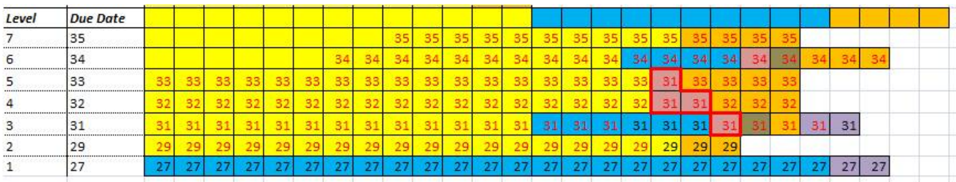


(a) Simulation. (b) Basic.

Figure 5.15. Cost split for higher shipment weight simulation, first horizon.

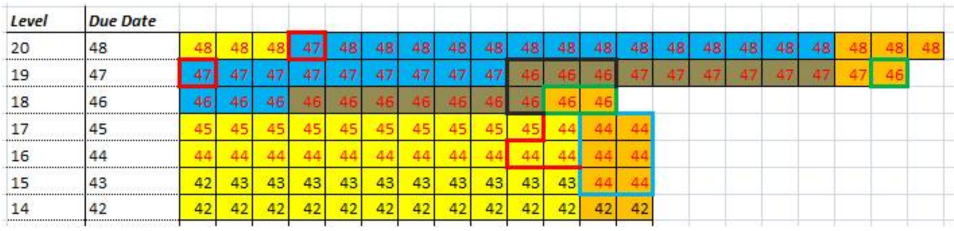


(a) Production plan.



(b) Shipment plan.

Figure 5.16. Production and shipment plan for higher shipment weight simulation, first horizon.



Level	Due Date																					
20	48	48	48	48	47	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48
19	47	47	47	47	47	47	47	47	47	47	46	46	46	47	47	47	47	47	47	47	46	
18	46	46	46	46	46	46	46	46	46	46	46	46	46									
17	45	45	45	45	45	45	45	45	45	45	45	44	44	44								
16	44	44	44	44	44	44	44	44	44	44	44	44	44	44								
15	43	42	43	43	43	43	43	43	43	43	43	43	44	44								
14	42	42	42	42	42	42	42	42	42	42	42	42	42	42								

(a) Greener solution.

Level	Due Date																					
20	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48
19	47	47	47	47	47	47	47	47	47	47	47	47	47	47	47	47	47	47	47	47	46	
18	46	46	46	46	46	46	46	46	46	46	46	46	46									
17	45	45	45	45	45	45	45	45	45	45	45	45	44	44								
16	44	44	44	44	44	44	44	44	44	44	44	44	44	44								
15	43	42	43	43	43	43	43	43	43	43	43	43	44	44								
14	42	42	42	42	42	42	42	42	42	42	42	42	42	42								

(b) Basic solution.

Figure 5.17. Shipment plans for green simulation and the basic one.

5.4 Greening the project

In the curtain wall market a great importance is given to the environmental theme, so much that clients require specific certifications to assess the sustainability of the project processes, such as *Breem* or *Leed* requirements (BREEM, 2016; Green Building Conucil Italia, 2016). For this reason, the company can decide to run the project with a grater impact of the transport cost, in order to take into account not only the economic aspect, but also the environmental one.

This simulation shows the result on the shipments, when the transport cost is being tripled from 52.5 € to 157.5 € each truck. The new shipment plan can be seen in picture 5.17, where the result for the basic configuration is also shown. The solution proposed effectivey points to trucks space fulfilment, since we have 2 additional groupings respect to the basic configuration:

- black squared packs: level 19 shipment has been anticipated respect to the due date in order to reduce the empty space of the trucks, which can be filled up to 5/6 of the capacity;
- red squared items: one pack of level 17 has been anticipated to week 44 in order to completely fulfill a truck.

Table 5.7 contains the comparison between the two configurations in terms of full and less than truck load transports (in this case the percentage of fulfillment is reported). It is evident that this configuration is greener than the basic one: the waste volume is 152.72 m^3 against 412.16 m^3, which turns

Table 5.7. Number of full (F) and less-than-load (LTL) transports in green and basic configurations.

	week 44		week 45		week 46		week 47		week 48	
	F	*LTL*	*F*	*LTL*	*F*	*LTL*	*F*	*LTL*	*F*	*LTL*
Green	6	-	3	1(50%)	3	2(1x66%, 1x50%)	6	3(1x66%)	9	-
Basic	5	1 (66%)	3	1(33%)	3	2(1x17%, 1x50%)	5	3(1x33%, 2x50%)	8	1 (50%)

into a smaller amount of trucks to be sent to site, thus reducing transport carbon dioxide equivalent emissions.

5.5 Absence of Learning-Forgetting Effect

The aim of this simulation is to study the differences between the basic configuration result and the ones suggested by the model when no learning effect is taken into account, stated the same input data.

The production time for packs belonging to the same family product *k* in period *j*, *t[k,j]* is simply given by the multiplying of the standard time required $\bar{T}_k$, set in TypeInfo[k,r] table (4.6) and the number of units contained in each pack *i* (see GeneralInfo[i,r] table 4.4), as per equation 5.1, where N is the set of all of the packs *i* of the project:

$$t[k,j] = \bar{T}[k] \sum_{i \in N : GeneralInfo[i,2]=k} production[i,j] \cdot \text{GeneralInfo[i,4]} \quad (5.1)$$

No learning effect means that there are no differences in production time of the units at the start of the production batch, nor at the beginning of the production after a break. In coherence with this principle, equation 5.1 implies that time required to produce a unit is embodied by a unique value $\bar{T}_k$, independently from its production planning slot.

With this hypothesis, new objective function value is 20771.99 €, which is 22.2% less than the one in the basic configuration. Cost split can be seen in figure 5.19a, where it is noticeable that the pattern with the basic configuration is very similar. The planning proposal is reported in figure 5.18, where packs are simply executed as per input sequence.

Along with the cost impact, time planning has a great evidence since in this configuration, the plan foresees to produce 45 packs with a capacity of 12 people. Moreover, as it can be seen in picture 5.18, production can start in period 25, one period after the basic configuration, so the planning is squeezed but not physically feasible. As explained in chapter 3 ad supported by this simulation, it is fundamental to insert learning-forgetting phenomenon in order to take into consideration the physiological limits of the workers, which turns in feasible cycle times, correct resource planning and reliable costs budgeting. In fact the standard configuration can be misleading both

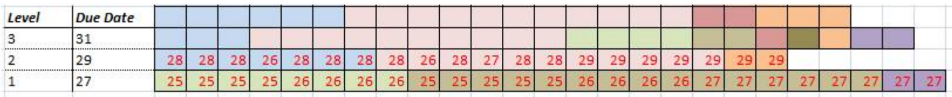
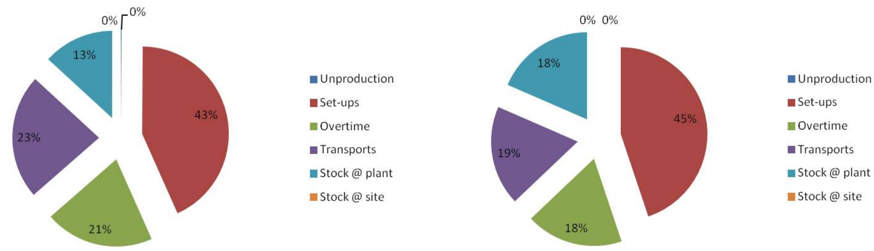


Figure 5.18. Production plan for simulation with standard times, first horizon (25 to 29).



(a) Standard. (b) Basic.

Figure 5.19. Comparison between total cost split for standard time simulation an basic.

in terms if planning and in terms of costs: it calculates an average cost of approximately 461€/pack against the 668€/pack that are provided by the basic results.

Chapter 6

Conclusions

Achieving sustainability-related targets in Construction Projects is increasingly becoming a key performance driver, therefore stakeholders are paying more and more attention to environmental strategy and environmental impact assessment. In this scenario the concept of the triple bottom line by Elkington (1998) comes to the surface, so that Construction is said to be sustainable when it meets environmental challenges, responds to social and cultural demands and delivers economic improvement. When dealing with this market, which is recognised to be one of the most dynamic, risky and challenging business sectors, the companies playing the role are the Project-Based ones (PBE), in which the core business is represented by the development of project where innovation and planning have to cohabit in order to reach high performances and sustainability levels without neglecting the control of the efficiency dimension.

In Construction PBEs, the activities involving every department lead to manage significant trade-offs, since each construction project, due to its unique characterization, has plenty of custom elements to be designed and purchased with low repetitiveness rates and engineer to order components to be produced. Each floor of the building is associated to a contractual hand-over date, which pulls and determines the activities of the upstream supply chain in order to avoid extra-costs and disruptions or the application of penalties by the client because of installation delays. The entity of the extra-overs that may incur depend on the contractual conditions of each project but they can reach the magnitude of hundreds of thousand of euros. In the light of this, a model that can support decision-making to mitigate the contractual risk is necessary. Despite the need for a synoptic view on the economic, environmental and social themes, which must be addressed to perform Projects with high profitability to offer the company a competitive and long-lasting advantage, there is a lack of planning and decision-making tools that can offer companies a all-at-once glance on their Operations processes.

In this thesis a new model for the production planning in construction Project Based Enterprises has been developed by considering the three dimensions of sustainability, and applied to a worldwide leading company of the Curtain Wall sector, *Permasteelisa Group*, which is an excellence operating in the North East of Italy and that gave the availability to suitable interviews, data analysis, production reports, project specifications and contractual intents. Along with the definition of the best sustainable production plan, the model intends to be a decision support tool since the company can test, through different simulations, whether it is necessary and worthy to pay for a storage area where to stock the produced units, as well as gathering a resouce planning and comparing the different contractual forms that an awarded project can be subject to.

The economic result can be enhanced by maximizing the production of items, by taking into account the idle time of the assembly line along with the time related to set-ups and overrun. From the environmental point of view, since each element has a unique location on the building to be handover to the client within specific delivery dates set into the contractual program, the number of transports in a project is strictly linked to the production sequence and it has to be taken into account during the planning phase, thus mirroring the installation program because of the limited area reserved to logistics on installation site. Hence in the model, it has to be considered that production optimization has direct implication on the fulfillment of the means of transport, which have to be fulfilled as much as possible to reduce GHG emissions along with costs. The social theme of the TBL is addressed in the production planning through the learn-forget curve model, suitable for limited productions, which are typical of PBEs, especially when referring to the curtain wall sector because of the strong requirement for elements to be packed according to the installation sequence on site. By inserting the learning-forgetting curve into the production planning model, more realistic cycle times can be calculated and managed, thus reducing the work stress of the personnel thanks to feasible plans and making factory environment more friendly, therefore improving performances. Thus, one typology can be produced in more than one batch during the time horizon by alternating it with the other typologies of the building, by leading workers to improve their performances according to the production sequence, which mixes up the various typologies of elements by taking into account the due dates stated on the project program. Moreover the planning on the horizon shows the real production capacity of the assembly line, by making more reliable forecasts during the project planning definition. As highlighted by M.Brandenburg et al. (2014) in their literature review, holistic approaches in SSCM that reflect all three sustainability dimensions are relatively rare, even if empirical research shows the growing relevance of multiple sustainability aspects: SSCM research tends to focus primarily on environmental issues, while social facets are widely neglected in empirical and analytical modelling research. In this sense, it is significantly important to take care of the social aspect of the triple bottom line when drawing up the production schedule of a construction project. In the light of this, by inspiring by Jaber M.Y. (1996), three Permasteelisa curtain wall projects have been analysed in their production reports and evidences of the learning-forgetting phenomenon have been recognized and studied in order to find out the suitable parameters that the model should take into account when performing the best production plan. As an outcome, the lack of consideration of the learning-forgetting phenomenon in the production planning is misleading since the production time is under-estimated up to 69%, with negative consequences on the actual planning in terms of time and capacity on the assembly line, causing delays on the general Project Plan.

The problem has been solved by using the Constraint Programming, because of the unlimited type of relations between variables that a modeler can adopt and because of the easy editing, thanks to the separation between the modelling and solving phases. This flexibility can be really useful when dealing with PBEs, since every project has its own specific features to be defined into the general production planning model. The Objective Function has been build with different terms that allow to embrace the three dimensions of sustainability on cost bases, so that the social and environmental aspects can be compared to the economic one in an objective way. This gives the opportunity to focus simultaneously on the three aspects with the minimizing of the cost, which is the final aim to be achieved by companies. Hence, the cost items that compose the Objective Function are: (i) unproduction; (ii) set-ups; (iii) overtime; (iv) less-than-truck load transports; (v) capital costs.

The model has been applied to Manchester One Spinningfields Building, a 20,000 m^2 curtain wall project awarded by Permasteelisa Group and the following pieces of information have been gained:

- assembly production and shipment weekly plans;
- different impact between the two most common contractual forms;
- storage capacity which should be equipped on site and in the production plant;
- magnitude of the overtime that the company has to consider to make the project feasible;
- total loss forecast of the project due to contractual, production and logistics issues.

The results show that the total loss for the company is 250,382.92 € over 5 planning horizons, which represent a total of 25 weeks of production for this project. The major cost item is due to set-ups (33%), followed by transport

(29%), unproduction (16%), capital costs (13%) and finally overtime (8%). As an evidence, in the basic configuration the pattern of the model is to minimize as much as possible the unproduction of the assembly line and the storage at installation site. The learning-forgetting phenomenon is taken into account in several occasions through the anticipation of the production of item belonging to the same family product.

In general, the tool that have been proposed in this thesis can be useful to take proper decisions both on the tactical level, with the suggestion of a production plan and on the strategic level, according to the company-strategy. From this latter point of view, several simulations have been performed to assess the deviations from the basic configuration. By changing the contract type the model can address the firm in the assessment of the best contractual agreement with the client. By balancing the activities in different ways, the planning can be modelled accoding to the contractual scope of work. With main evidence on the environmental issue, the model allows the company to run the project with a greater impact of the transport cost, in order to take into a different perspective if the client asks for strongly eco-friendly performances. One more simulation has been run to verify the impact of neglecting the learning-forgetting phenomenon in the production times: results show a squeezed planning which is not physically feasible and bearable by the workers, thus giving a misleading support both in terms of time and costs.

As for the future developments, the model can be tested and applied on a brand new starting job in order to obtain a mid-term fasible and reliable program which can be the base for the development of a new model that can help the company on operational level. In this context, a production schedule can be created to understand effectively how to fulfill trucks, i.e. to define the packing list of each mean of transport, and how to effectively alternate the various typologies on the assembly line day by day. By adding this latest tool, the model can assist the firm on three levels, strategic, tactical and operational, giving then the chance to integrate the several phases of the project life-cycle at the best.

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