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Flexible Field Factory for Construction Industry

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ABSTRACT

Purpose – In this paper we present the concept, the layout design, and the evaluation performed of a Flexible Field Factory for the Construction Industry. Both the concept and layout are focused on flexibility and mobility factors, providing a versatile system for manufacturing and assembly that can be transported to construction sites without need of special permissions.

Design/methodology/approach – The design itself is based on the Design For Manufacture and Assembly (DFMA) principles, Lean manufacturing, and construction industry experts' knowledge.

Findings – The developed factory layout is dimensioned to fit in a standard 20-feet-long container. Simulation processes have been run to verify the viability of the system. The time estimates calculated in the simulations are compared with traditional in and off-site construction method estimates, providing quantified cost and time benefits.

Originality/value – This paper present the concept of the robotized Field Factory designed for on-site prefabrication, which design began during the EU 6FP ManuBuild Project. This reconfigurable and flexible system is oriented to the production of small and medium size modular systems. The viability of the Field Factory has been evaluated thanks to the application of a modular system for building installations called Service Core. Its design has been based on DFMA and Lean principles as well as the expertise from construction partners from ManuBuild Project.

Keywords: Modular Assembly, Robotics, DFMA, Lean, Building Industrialisation

INTRODUCTION

The construction industry is known for being an extremely traditionalist and conservative industry; there are those who even question its nature as an industry. It is attributed with the employment of methods that are thousands of years old, not having evolved sufficiently towards more industrialised methods of construction (Mora, 2007). In the past 50 years, construction has experienced industrial advances in two directions.

On one hand, numerous materials, product of general industrial advances in other industrial sectors, have been incorporated. On the other hand, work at construction sites has experienced a process of accelerated mechanisation which, in developed countries, has greatly diminished labour at the site and furthermore improved the work conditions for the labour that still persists.

The goal of this paper is to present the results of the research performed in the Systems Engineering and Automation Department focused on the industrialization of construction methods, which began within the FP6 EU-Project ManuBuild. The industry driven goal of the ManuBuild project is to create an Open Building Manufacturing paradigm (Kazi et al., 2009) through the combination of ultra-efficient manufacturing in factories and at construction sites, ultra-new robotics and intelligent systems, and an open system for products and components, offering the diversity of supply in the open European market. The project aims at combining unconstrained building design with highly efficient industrialised production. The foundations of this paradigm are to be underpinned by enabling business processes, ICT systems, new materials and technologies, and smart components (Martinez et al., 2008).

The aim of this work, carried out during the ManuBuild project, has been to develop and test the flexible and autonomous Flexible Field Factory for on-site automatic manufacturing and assembly of pre-fabricated parts and systems. The Field Factory will bring efficient manufacturing and pre-assembly operations to building sites, providing safe and clean working environments, and drastically reducing the number of transport kilometres between the factory and the building site. Optimization of transportation, installation and dismantling costs, the applied Just-In-Time (JIT) concept (Hutchins, 1999)(Tommelein, 1999), and flexible adaptation for changes in processes are key aspects that may be provided by the Mobile Factory, and are studied quantitatively and qualitatively throughout the extension of this article.

THE FLEXIBLE FIELD FACTORY CONCEPT

Each construction site can truly be considered a complete and complex assembly plant (Ballard and Howell, 1998), and is habitually unique for each building. This assembly plant produces one, single, product: the building. This means that for each building, a new assembly plant is mounted, and, at the end of the construction cycle, it must be disassembled. The cost of component transport and the costs of implantation and disassembly at the construction site play a relevant role in the construction of buildings.

The Flexible Field Factory is a container-based factory that is moved from one site to another by a truck (as can be seen in Figure 1). The walls of the container are capable of opening and resting on its sides providing extra work surface for the deployed on-board equipment. The system has been designed to be transported in a 20” (6 m long) standard container in order to avoid the need of special transportation permissions.

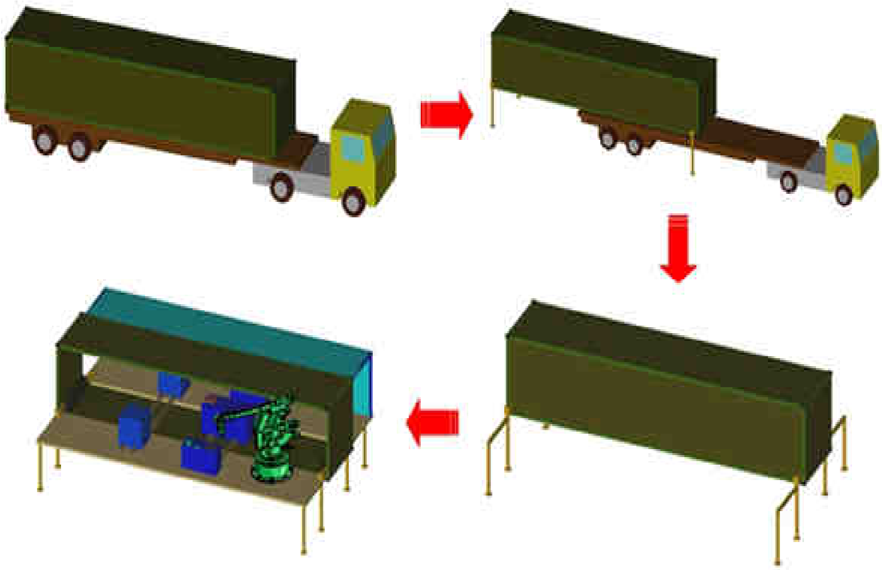

Figure 1 The Flexible Field Factory Concept

Implicit in its definition is autonomy in energy, operation, and management. The factory is flexible and reconfigurable for multipurpose on-site activities and materials, while providing a safe working environment as it works as a mobile secured robot cell.

Task oriented concept

One of the main considerations in the design of the Flexible Field Factory has been the Design for Manufacture and Assembly (DFMA) principle. DFMA is aimed at ensuring the technological and economic feasibility of product manufacture and assembly

(Mileas and Swift, 1998). The basic tasks that the automatic Flexible Field Factory system must perform in a construction site are the base of its design. In consonance with the DFMA principle, these tasks may be carried out individually, or compositely, in a multi-task system, creating the complete process workflow of the Field Factory. The basic activities considered are the following.

- Preparation. The very first task the system must accomplish must be the preparation of the materials that will be manipulated. Correct preparation will increase the performance and quality of the final product.
- Machining small and medium sized pieces. In the construction industry, machining of pieces is one of the main processes performed before assembly. For instance, the different sizes between slabs and the dimensions of the walls, floors and roofs they will cover make some machining tasks (such as cutting) indispensable.
- Assembly. Assembly tasks consist of the union of two or more constructive elements using a joining material or system. While it is obvious that the complexity of an assembling system is incremented by the need of additional tools for assembly, one of the main issues to solve during the design of this kind of system is the fixation mechanism. Two parameters are critical:
    a. The method of assembly. The way to perform the union of materials must be clean and fast. Due to this, mechanical fastening has been selected.
    b. Permanence of the assembly. The final product features will determine if permanent or reversible unions are recommended.

  Considering the ManuBuild construction experts' opinion (E.U. Project partner Dragados) and the robot-based machining orientation of the Field Factory, extra focus was set on fast-fit connectors as mechanical fixing elements (Orton, 2003).
- Finishing. Finishing operations aim at endowing materials with their desired final properties (Massarsky and Davidson, 1997). These final properties can vary in nature, as they may be purely aesthetic properties, or chemical or mechanical properties to create resistance to corrosion or physical impact.

Additionally, the product components are designed (or selected) to be manufactured and assembled by the specific system, thus eliminating re-design and waste costs, according to Lean manufacturing principles (Howell, 1999).

Flexible Field Factory Design

The Task Oriented Design described in the previous section is a key aspect of the Flexible Field Factory system concept and design. Although these characteristics do not have a strong influence on the design of the final layout, they determine how work must be performed and provide some necessary characteristics for tool selection. The following additional characteristics are fundamental.

- Flexibility. The Field Factory must be flexible enough to be used in several operations. It may not be restricted to performing a single task. We shall define flexibility as the capability of a factory of performing different tasks and products without significant changes in its mechanical system. Flexibility must be shown in two aspects.
    a. On tasks: The Field Factory must perform a range of tasks in a flexible way. This means that the process flow and order in which tasks are performed may vary, depending which activity is being performed. On the other hand, the work carried out must follow natural sequences of performance, in other words, the sequence of tasks must be logical, preventing impossible sequences from being performed. This restricts flexibility and the possibility of combining and generating sequences of tasks.
    b. On products: The machinery used in the Field Factory must be capable of working with different types of materials at the same time, or to be able to change tools in order to fulfil this requirement.
- Safety. The Field Factory safeguarding system should protect not only the operators but also engineers, programmers, maintenance personnel, and any other workers near the automated system work area. A combination of safeguarding methods may be used. Redundancy and backup systems are especially recommended, particularly if the system is operating in hazardous conditions or handling hazardous materials.

- Reconfigurable. The Field Factory should be reconfigured using any of two different mechanisms. The first one is via software, modifying the sequence of tasks which it must perform, which can be combined to generate different process workflows maintaining the system mounted. The second is physical reconfiguration so that the tools and materials can be adapted to the assembly process. This modification only can be applied during the Field Factory layout design stage: late modifications in the mechanical architecture of the Field Factory could not be possible without dismantling the system.
- Multipurpose. This feature is closely linked to flexibility regarding tasks. The Field Factory must not only be able to perform a single kind or sequence of tasks; it must be capable of performing a wide range of tasks. Therefore, the machinery used must be multipurpose. It must allow the use of different tools for different types of material and processes. On the other hand, this feature also means that the Field Factory must be capable of manufacturing a range of finished product types.

The final physical layout takes all the previous statements into full account, with a special emphasis on mobility. All of the space limitations and the design conditions of the Field Factory are therefore determined by the selected transport method, a truck-towed standard 20 foot (6 meter) long container, also known as TEU (Levinson, 2008). This intermodal container-based design allows an easy transportation without special permissions. When in transportation mode, there is approximately 39.6 square meters of available surface for machinery and materials. Once at the construction site and expanded, a total of 76 square meters of working area is available for the machinery to be placed and the product produced. Figure 2 depicts a bird’s eye view of the Field Factory, using the real dimensions of the TEU as design parameters for its final layout.

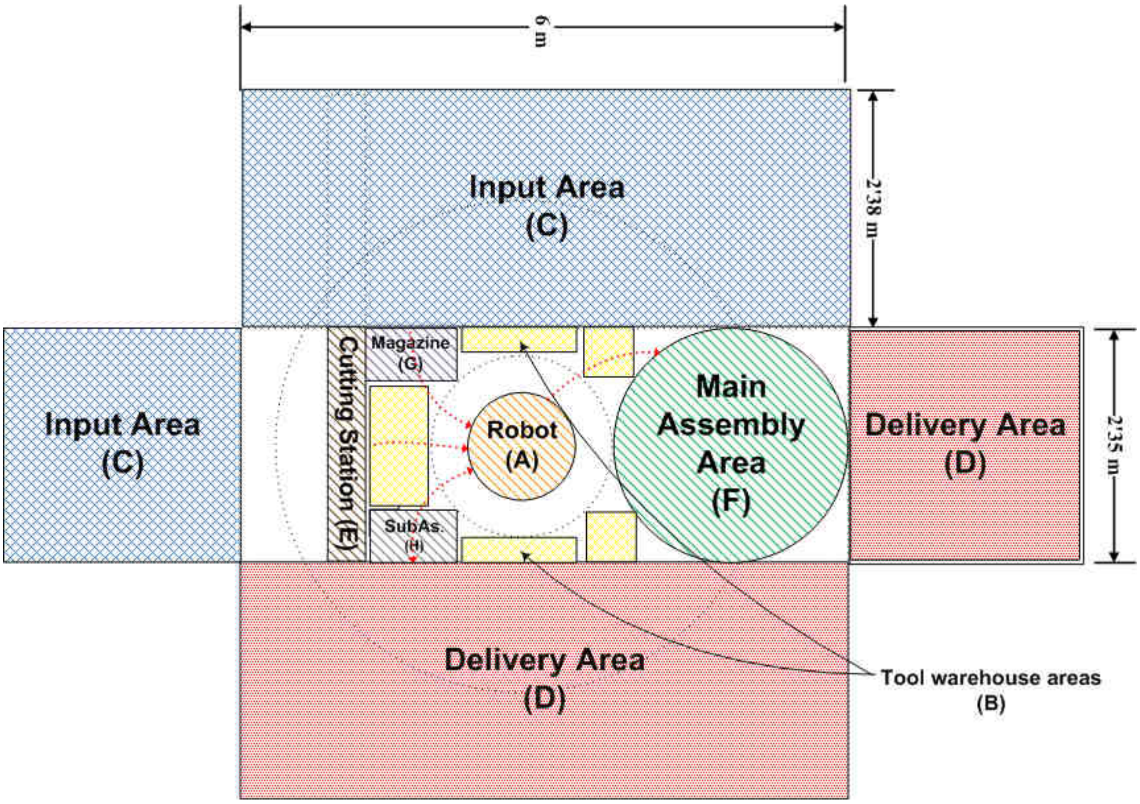

Figure 2 Field Factory Layout

The Field Factory system design has been based on the flexible U-shaped work cell layout for production lines (Miltenburg, 2001), and modified due to its DFMA task oriented philosophy. In Figure 2, the robotic cell is composed by an ABB IRB6400/60 robot (A), five tool warehouse areas (B), two material inputs (C) and two delivery zones (D). Four processing stations are integrated into the layout: cutting station (E), main assembly area (F), magazine and small parts handling (G) and the subassembly area (H). The system has been designed to work in semi-automatic mode. The human factor is taken in account for feeding and unloading tasks. Human activity inside the robotic cell is prohibited for security reasons.

This layout is based on a robotic cell in a flexible and non-constrained fashion. The cell can perform assembly, machining or handling tasks independently or in combination with other machines. The system can be easily modified, replacing any of its parts by any kind of specific machinery to perform tasks. On other hand, the robotic system provides software and hardware flexibility through the use of programming and simulation environments and through the use of interchangeable tool systems, respectively, enhancing the variety of possible workflows.

EVALUATION OF THE FLEXIBLE FIELD FACTORY

The following step after establishing the concept and designing the final layout of the Flexible Field Factory is to verify the viability of the system prior to its implementation. In order to perform this verification, a simulation process has been run, and its results have been compared with data obtained from the construction of real 3D modules using the methods that are currently used in the vast majority of real construction sites.

The simulation processes have been performed in two stages or levels, the first one at product level, and the second one at system level. In the first level, the product called 'Service Core' was selected as a demonstrator inside the ManuBuild Project, to test the system performance. It is a 3D frame, built to support and incorporate sanitary water installations, drainage installations, etc. The Service Core has been assembled using traditional techniques and analysed with the goal of adapting it to an automatized assembly. The most relevant result has been the final product redesign taking the DFMA principles into account. The resulting adaptation leads to an efficient automated production by the Flexible Field Factory system. The simulations have been performed with Dosimis-3^{TM} software (Ziems et al., 1993). The aim of these simulations has been to obtain time of production comparisons.

The second level taken into account was the operation of the system inside the construction industry. One of the most important aspects of any production system has been simulated: the logistics. Three scenarios, in which several Service Cores must be produced and installed in different sites, have been established. The main goal of this second set of simulations has been to get logistics time and cost of operation data to analyse the viability of the Flexible Field Factory system inside the construction industry.

A product for evaluation: Service Core

During the development of the ManuBuild project, several products were studied and developed in order to evaluate different aspects and elements of the industrialization of the construction industry. One of them was the element known as the 'Service Core'. It is composed by a 3D metallic frame to which all of the necessary services for the operation of bathrooms, utility areas, or even kitchens are attached. The Service Core essentially contains much of the equipment that would otherwise be field-installed in a house, such as plumbing lines, HVAC ducts, and fixtures. The efficiency of the production of this type of system to make the facilities of the services in a house has been proved, especially in multi-storey housing (Martinez et al., 2008). The complexity and modularity of the Service Core match with the ManuBuild philosophy regarding industrialized and modular construction systems.

The current process for Service Core production

Nowadays, Service Core modules are assembled on site, manually. Specialized installers (plumbers, etc.) build each different service network over a pre-assembled frame. Then, the modules are transported to the building and joint to the other modules to compose the so called 'wet wall'. Inside the ManuBuild Project, a Service Core module has been manufactured using conventional methods and a full team to validate the concept, study its design, and make improvements.

The assembly process of a Service Core module is typically sequential. It starts with the manufacturing of the metallic frame. This is usually performed in a workshop outside of the construction site, and is then transported there. The next step is the service installation assembly. Installers with different knowledge are needed in the assembly process, depending on the type of installation. After a module is complete (see Figure 3, right), it is transported to the building and installed inside (Figure 3, left).

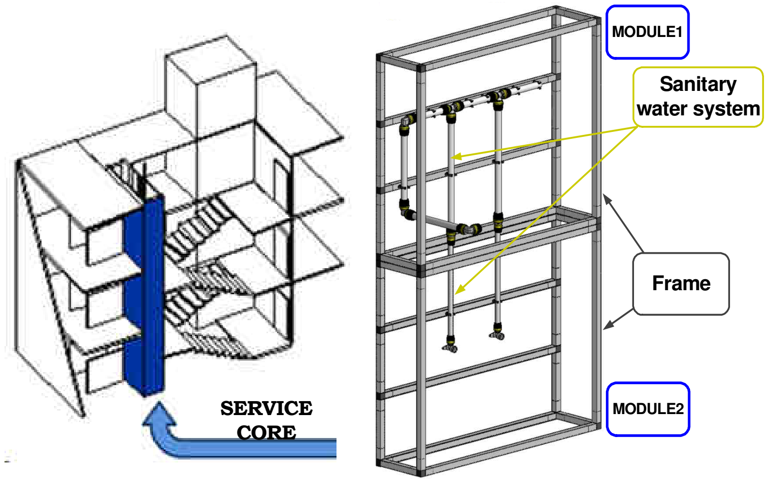

Figure 3 Service Core and 'wet area'

Once the Service Core module was built, the resulting data was analysed, and several interesting conclusions were extracted:

- The modules are not assembled in parallel. Each installer works on a single module independently: never do two specialists of different areas work on the same module. This is a clear bottleneck in the process.
- The work time in manual assembly is not continuous. There are rests and delays that increment the global assembly process time.
- In the case of 3D structures shipping (metallic frames), the transport costs are greater than transport raw material due to the necessary 'air transportation'.
- Preparation time of the tools and materials is included in the overall work time.
- The adaptation of each installation to the frame makes the addition of extra parts to the frame for supporting the structures necessary.
- The quality of the finished Service Core depends on the experience and the skill of each installer.

Neither the raw material supply time nor the frame transport time from the factory to the site was taken into account. Only assembly and rest time was considered.

Automatized process for Service Core production

After the assembly of the prototype, the Service Core was analysed to improve the overall assembly time and quality, applying DFMA concepts. The result has been a new 3D module with new components that, joined with a new assembly process workflow, enable its automatic assembly by the Flexible Field Factory. Prior to the physical automated fabrication of the new Service Core, its assembly process has been simulated using estimated process times, taken from similar processes in other industrial areas.

The new process has been modelled using Dosimis-3^{TM} software. As presented in Figure 4, the model has been divided into five clearly differenced sectors.

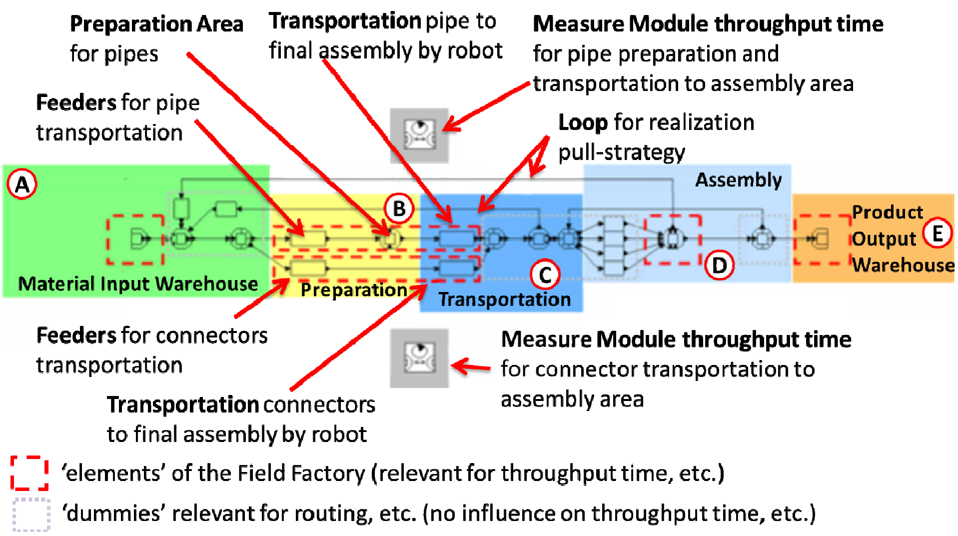

Figure 4 Field Factory Simulation model (Courtesy of Fraunhofer IAO & UC3M)

The system input is represented by a 'source' element in the simulation model. All of the parts that are necessary for the assembly of the frame are generated in this source. All of the other elements within the "Material Input Warehouse" sector (Figure 4, (A)) are either relevant for part routing or are additional necessary elements due to that all work within the Flexible Field Factory is performed by a robot.

The "preparation area" (Figure 4, (B)) is composed by two lines. One line is for the tubes and pipes, and the other line is for the connectors and clamps. Connectors and clamps are transported in a first stage by a 'feeder' in the Field Factory; tubes and pipes are transported with aid of a feeder to the preparation station, where the parts are cut and cleaned.

The “transportation assembly” area (Figure 4, (C)) is responsible for the transportation of the material. This step is also performed by the robot. Transportation time is aggregated in the feeders. The other parts are ‘dummy’ elements that have no influence on the throughput time or on other parameters.

The assembly of the frame and the installations is performed sequentially, by means of an industrial robot arm. In a first step, the frame is assembled. Then, the different installations are integrated into the finalised frame by means of the sequential assembly of tubes and clamps. Within the simulation model, the assembly area is represented by the “assembly station” (Figure 4, (D)). The additional elements of this sector are also dummy parts and are not part of the real Flexible Field Factory, but are relevant for the model as described above. At the assembly station, the time for joining the tubes, pipes and the connectors, and the time for fixing the installations on the frame are considered.

The finalised frame is then transported outside of the Field Factory. This is represented by the ‘sink’ of the “product output warehouse” (Figure 4, (E)) in the simulation model.

Results analysis

There are some considerations that must be taken into account before commencing a comparison between the manual and the automated process. This is mainly due to the differences between:

- Methods of assembly. Fast assembly methods are easier to automate than traditional ones, i.e. fast-fit connections versus glued junctions. Fast-fit connections increase the velocity of the process while achieving a better finish. Traditional and manual assembly methods are subordinated to the installer’s skills.
- Wasted time. There are innumerable causes that can lead to time loss in manual assembly processes. This includes not only planned times for rest, but also re-

planning on site or decrease in work performance caused by fatigue, to give just a few examples.

The time results extracted from the processes can be viewed in

Table 1.

Table 1 – Time Comparison: Automated versus Manual, process times in minutes

	Automated Process		Manual Process	
	Preparation	Assembly	Prototype	Reduced
Frame	105.39	28.01	480	336
Drainage	65.36	22.34	300	210
Sanitary water	105.57	37.67	420+360	252+210
Subtotal	276.32	88.02	1200	840
Service Core	364.34		1560	1092

As has been previously mentioned, there are differences derived from the experience and the skills of the installer on the assembly of these kinds of modules. The time used for the manual assembly of the prototype was 1560 minutes. However, it has been evaluated that excessive spare times and other time losses can be avoided, reducing the assembly time by about 30%. Taking this in account, the mean manual assembly time is then 1092 minutes.

In the case of manual assembly, the metallic frame was built in a workshop and transported to the site where all the installations were mounted. Only one person was in charge of the installation assembly process. The time needed for assembling the prototype was 1092 minutes (18.2 hours). If several Service Cores must be assembled in one site and assuming an 80% learning rate (Adler and Clark, 1991), the time mean needed for ten modules' assembly is 520.35 minutes per module. This reduction includes all of the operations needed for obtaining one complete Service Core. It is important to recall that no material supply problems, transport delays and other issues were taken into consideration in both processes.

The Service Core construction time, in the automated process, is 364.48 minutes (6 hours). This means there has been a reduction of approximately 67% of time related to the prototype assembly. Taking the learning rate in account the benefit is minimized to a 30% reduction, but starting from the assembly of the tenth Service Core. The differences between manual and automated process is caused by two main issues:

- Continuous operation. The automated system does not need time outs, and the performance of the tasks achieved is always the same.
- Duration of tasks. The repeatability of the automated tasks differs from that of the manual one. The velocity and duration of the task achieved by a person change depending on different external and personal factors.

APPLICATION OF THE FLEXIBLE FIELD FACTORY CONCEPT: LOGISTIC ISSUES

Until this moment, issues related with assembly and automation have been studied. But the operation of the Flexible Field Factory is strongly influenced by one of its core features: mobility. Logistics issues regarding operation of any system inside the building market are very important: restrictive laws related to transport, material handling, wastes in transportation, etc.

Due to this, once the automated system has been evaluated by means of a product assembly, the whole system must be evaluated in the building market to verify the benefits it brings. In order to perform this evaluation, three construction scenarios have been simulated and compared: two scenarios with current assembly processes, and the Flexible Field Factory scenario.

Evaluation of building scenarios

- **Problem formulation**

The problem formulation was conducted incrementally, in close cooperation with experts from the construction sector (E.U. Project partners Dragados) to ensure that the study's all-over objective and specific issues were addressed. Hence, the data

determined to be relevant for modelling have been the following: cycle times and transportation times, transportation distances, and logistic costs for different scenarios.
The models that have been developed are able to demonstrate exemplarily the influences of different logistic and production strategies for the assembly of Service Cores. These models cover all of the transportation process information related to the mentioned relevant factors. The preciseness of the input data was defined under consideration of the conceptual formulation.
Based on the discussion with the experts from the construction sector, three simulation models were designed: Flexible Field Factory, traditional assembly, and fixed factory scenarios. The models are a complete representation of the supply-chain strategies for the assembly of Service Cores, including limited minor simplifications. These simplifications have been carefully selected and were verified with experts in order to avoid simulation failures. The processes inside warehouses for raw material (sanitary water components, frame tubes, drainage parts...) were not within the scope of the simulation. Neither the storage costs of raw material nor of the assembled Service Core have been considered in the simulation. In these specific models, the assembly process inside the fixed factory has been considered the same as the Flexible Field Factory process.

The overall process for the installation of the Service Core for all scenarios is fully comparable. Starting with the factory and the warehouses for the raw material, the components will be delivered to the assembly area for the Service Core and, after assembling the parts, the Service Core will be installed at the buildings. Each type of raw material is delivered with a truck to the assembly area. These four transportation processes are independent from each other.

The models do not take bottlenecks in the material supply into account. Bottlenecks in transportation (i.e. maintenance-times for the trucks or lack of availability) are not considered. Exemplarily, a number of three building sites for the test case were chosen, and the installation of five Service Cores at each building site was simulated and compared. The Service Core unit assembly time obtained from previous simulations was applied in each scenario. The specific details (scope and the logistic concepts) of each working scenario will be described within the following section.

- **Model programming**

- Scenario I: Flexible Field Factory (see Figure 5). This model is divided into four main parts. The 'raw material support' section represents the different warehouses and the factory of the physical model. For the realisation in the simulator, 'sources' are used. The processes in the warehouses and the factory were not within the scope of the study. The disposal of goods is not a bottleneck in the simulation system.

  The transportation section for the raw material is programmed with four loops that represent the road sections between the raw material support and the building sites. The distances for the road section were produced with a random number generator. The range for the generation of these distances has been set between 25 km and 100 km. The average speed of the trucks is fixed at 60 km/h. The 'assembly building site' area represents the Flexible Field Factory. The 'Field Factory' sector corresponds to the road section of the Field Factory.

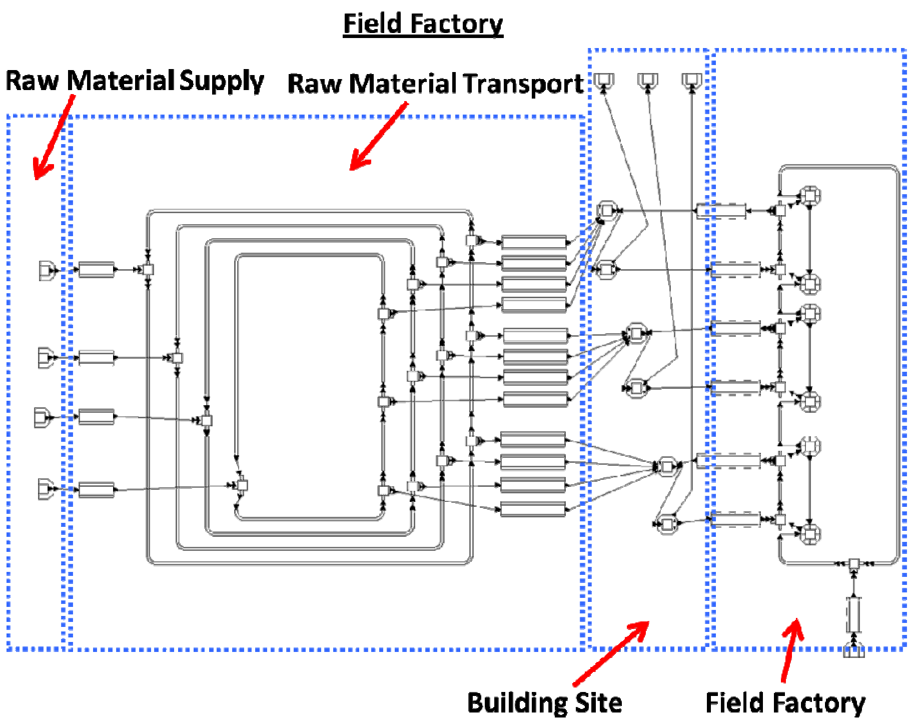

Figure 5 Flexible Field Factory simulation model (Courtesy of Fraunhofer IAO)

- Scenario II: Traditional assembly (see Figure 6). Raw material support and raw material transportation are exactly the same in this model as used in the Flexible Field Factory simulation model. The 'assembly building site' sector represents the installation and assembly of the Service Core in the buildings. Bottlenecks regarding unavailability of workers were not in the scope of the simulation and therefore are not implemented in the simulation model.

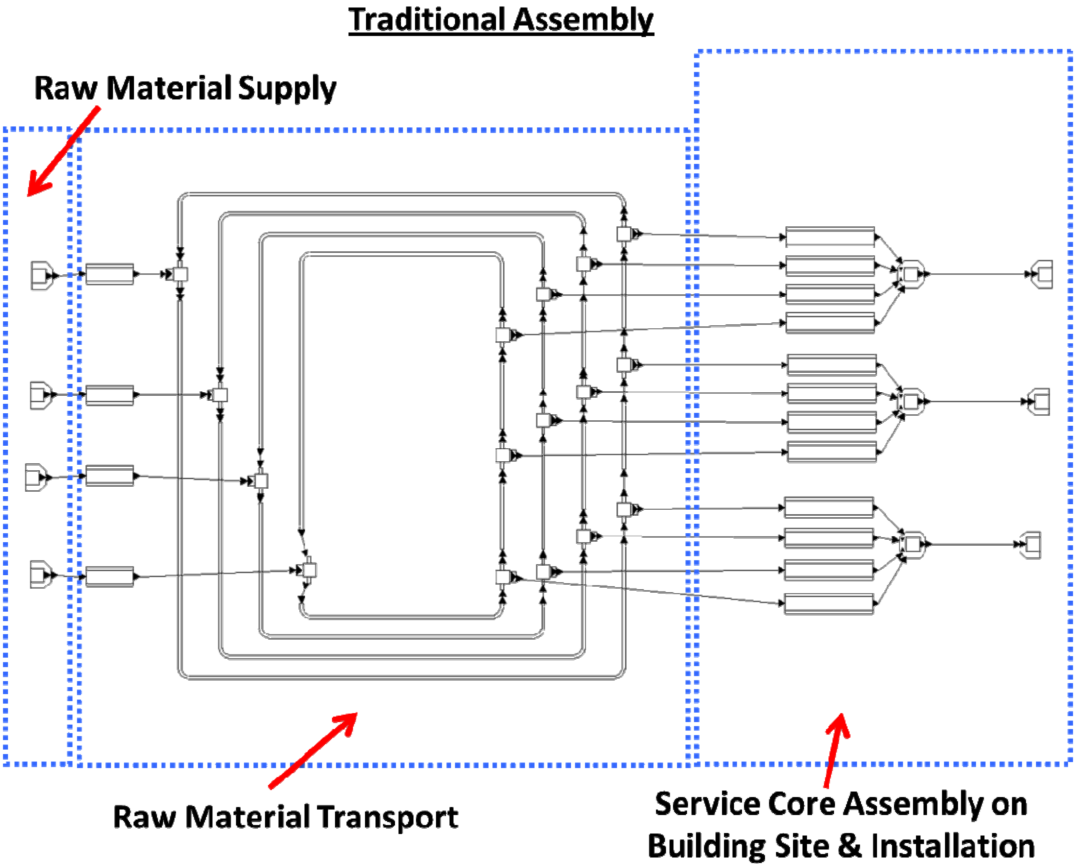

Figure 6 Traditional assembly simulation model (Courtesy of Fraunhofer IAO)

- Scenario III: Fixed factory (off-site production, see Figure 7). Raw material support and raw material transportation are comparable with that of the programmed model of the Flexible Field Factory, except for the distances of the road section. The fixed factory is modelled as a black box, only being parameterised with the assembly time of the Service Core. The transportation of the whole Service Core is implemented as one big loop where the assembled Service Cores can be unloaded one after another at the three building sites.

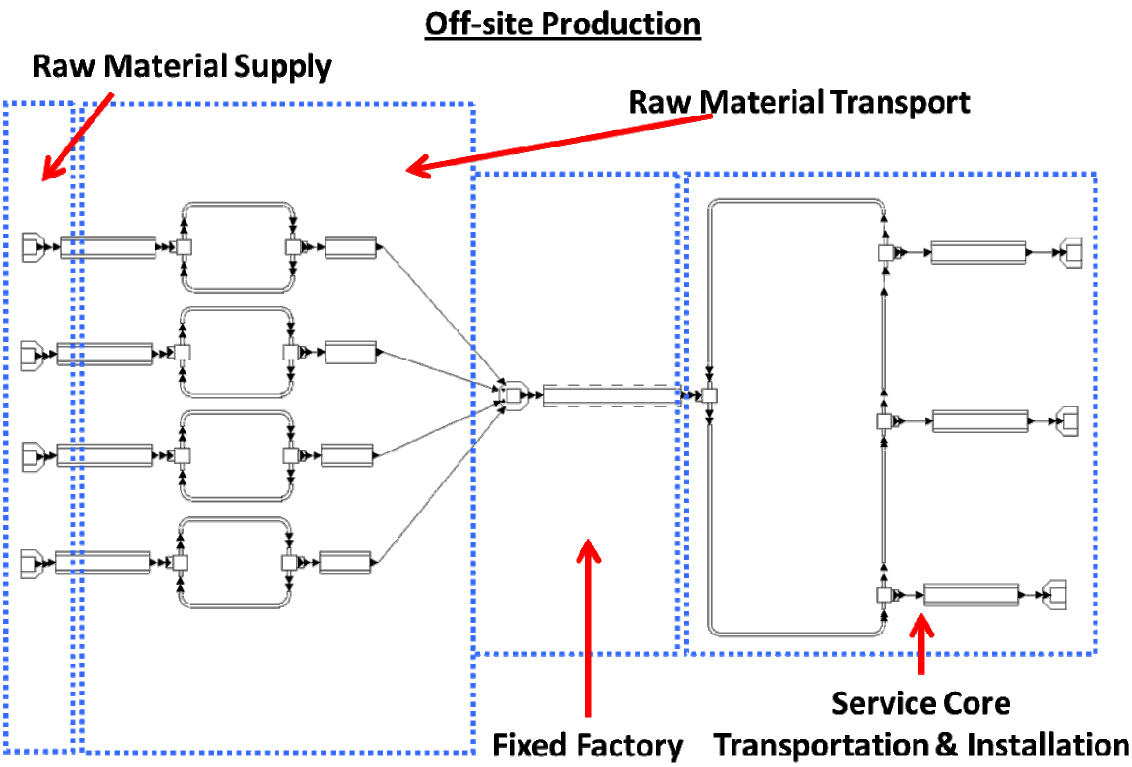

Figure 7 Fixed factory simulation model (Courtesy of Fraunhofer IAO)

- **Experimental planning**

The objective of the experimental planning was the comparison of the three different models and the analysis of the throughput times and costs of the three scenarios. Therefore a series of simulations were run for the models and the results were compared.

Analysis of the results

- **Service Core throughput time**

In a first step, the production time of the Service Core for each model was analysed and compared. Figure 8 depicts a comparative bar chart that indicates the throughput time of a single Service Core in days, including assembly and transportation times. Traditional assembly consumes much more time compared with the other two possibilities. The main reason for this is the different assembly method used.

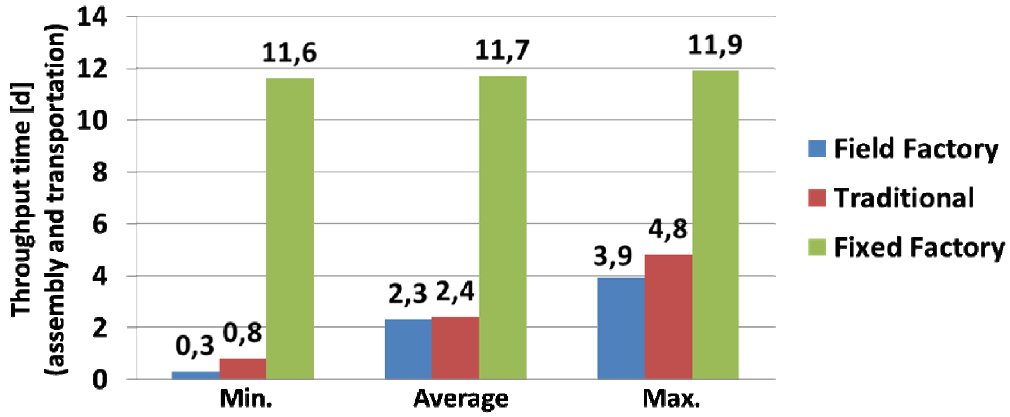

Figure 8 Comparison of throughput times for a single Service Core, including Logistics

Both the Flexible Field Factory and fixed factory produce Service Cores in an automated sequence. Therefore, there is no big difference between their minimal, average, and the maximal throughput time of a Service Core. Traditional assembly, on the other hand, due to the constraints and time wastes described in the previous sections, needs almost triple of the time for a single unit to be produced when assembly and transportation are considered.

- **Comparison of transportation costs**

In Figure 9, a comparative bar chart of the summarised transportation costs for raw material, transportation costs for the assembled Service Core (for the fixed factory scenario) and transportation costs for the Flexible Field Factory is depicted. The transportation costs are a direct function of the transportation distances. The comparison of the different scenarios shows that the Flexible Field Factory is the most expensive solution regarding transportation costs, followed by the traditional assembly. The cost difference of these two scenarios is 53%. The fixed factory scenario incurs the lowest costs for transportation (27% less than the transportation costs of the traditional assembly).

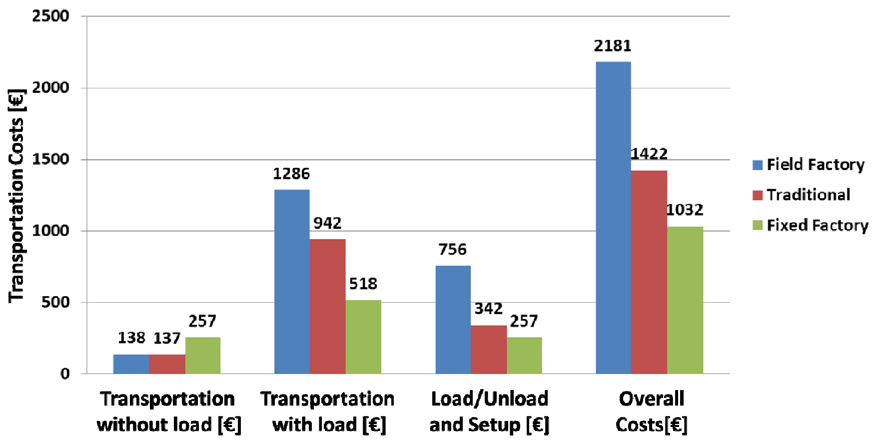

Figure 9 Comparison of transportation costs for the three different scenarios

- **Comparison of total costs**

The

Figure 10 shows the comparison of the total costs of the three logistic scenarios. Regarding assembly costs, the Flexible Field Factory is the cheapest solution, followed by the fixed factory. Traditional assembly, compared to the other scenarios, is the most expensive solution. Transportation costs have been analysed in the previous section.

The analysis of total costs, which may be interpreted as the sum of the total transportation costs and assembly costs, shows that the Flexible Field Factory is the cheapest solution for the assembly of 15 Service Cores at three different building sites. The Field Factory offers possible savings of 37% compared to the traditional assembly method. The fixed factory offers saving of 23% compared to traditional assembly.

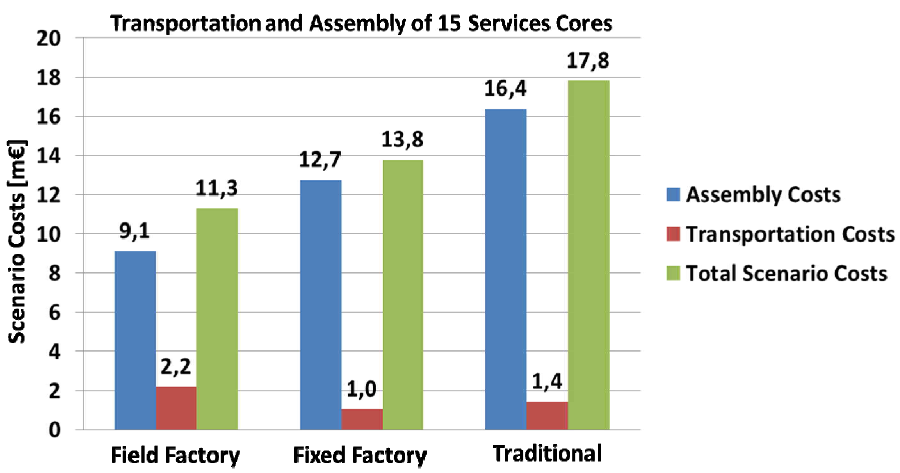

Figure 10 Comparison of total costs for the three different scenarios

CONCLUSIONS

The concept and final design layout of a Flexible Field Factory for the construction industry has been developed. The final concept of the Flexible Field Factory deals with the four following critical aspects.

- The creation of an adequate environment for manufacturing at the construction site.
- The mechanisation and rationalisation of production work.
- The mobility of the factory itself (without need of special permissions).
- Rapid reconfiguration for different tasks of the Field Factory.

These characteristics have been inherited and are intrinsic to the methodologies of design that have been used: the Lean and DFMA principles, focusing on creating a mobile, flexible, and safe platform, and maintaining strict attention to construction industry experts' know-how. The degree of final achievement of the initial objectives has been evaluated in terms of time and money savings. These results have been compared to other scenarios (a fixed factory for off-site pre-fabrication, and the application of traditional methods), offering substantial benefits compared to either one (up to 37%).

ACKNOWLEDGMENT

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