Abstract — This paper presents a manufacturing system of pre-fabricated panels for construction industry that has been developed for the Spanish company Dragados, S.A. The main contribution of the developed system is the automatic manufacturing programming, taking into account process restrictions, and using as input the architect’s 3D-drawing of the building done on a CAD system. From the CAD building design, the optimum facade to panels partition is obtained. In order to manufacture each panel and, based on CAD information, automatic task and path planning are performed for the equipment present in the robotized flexible manufacturing cell.

INTRODUCTION

Nowadays, construction industry is still well below the automation levels of other industries, although a rising effort has been made in last years. Applying automation in this important industrial sector is very difficult because of the non-repetitive processes, the low level of standardisation and the highly non-structured work-site environments. Construction activities can be divided into two main groups: off-site and on-site. On site processes are more relevant and form what is considered the typical construction work,
i.e. building. These activities are the most difficult in relation to automation, mainly because of the highly complex and variable environments in which they take place.

A common off-site process is the manufacturing of prefabricated facade panels (Fig. 1) that are later assembled on-site [1]. In last years one innovative material used in this kind of industry has been the Glass Reinforced Cement (GRC). Rapid design is a limiting factor in the production of GRC panels. Therefore a project to develop an automatic design of prefabricated panels from building design drawings was launched in 1994. The automated design system, now installed in a factory near Madrid, has been developed for Dragados S.A. with the financial support of the Spanish Ministry of Industry and Energy.

![Fig. 1 Typical building facade using GRC panels](image)

**PROBLEM STATEMENT**

A major aspect is the fact that the 3D geometry of panels changes very frequently. It requires a high degree of system flexibility. These variations depend on the architect’s
design and the building they are destined to. In the Dragados factory the average series for a given panel in the last 17 years has been of five units. Even if small differences between panels are not taken into account series do not exceed 50 units and only in very rare cases equal a hundred units. This diversity of geometries is inevitable in facade panels.

There are different panel types depending on the kind and number of layers to be sprayed. The first layer, which forms the external surface of the resulting panel, is common to all of them. It is done with mortar without fibre up to a total thickness of 2 mm. Depending on the remaining layers, there are five distinct types of panels (Fig. 2):

- **Plain shell:** two more layers of mortar and fibre up to a total thickness of 10 mm.
- **Shell with ribs:** same as plain shell but with stiffening ribs.
- **Stud frame:** same as plain shell but with a steel frame.
- **Shell with insulation:** same as plain shell but with insulation sheets.
- **Sandwich:** same as plain shell with insulation with and additional GRC top layer.
OBJECTIVE

From the preceding section it is clear that some kind of automation which improves building design flexibility is desirable. Therefore the objective of the automation project has been the development of an automatic system to manufacturing facade panels having as inputs the 3D CAD building design.

The production of pre-fabricated panels is done through several stages, of which rapid design is critical. Consequently, the first stage of automation has been focused on this issue [2].

Based on the experience obtained through the years of manual production the system is designed flexible enough to cope with small batch size production of different panels, integrating CAD and CAM. A great effort has been made to develop an integrated flexible low-cost system to be used on a range of similar applications, like modular building construction [3].
Today a highly flexible production unit, which is capable of manufacturing a big variety of small series under quasi-real time request, is crucial for most companies. This can be achieved in the manufacturing environment with the use of Flexible Manufacturing Systems (FMS) under Computer Integrated Manufacturing (CIM) [4]. This concept has been recently adapted to the construction industry introducing the Computer Integrated Construction (CIC) [5]. The development of an FMS for CIC has to consider the inherent barriers common to these kind of systems: 1) low level of reusability of software and/or hardware, 2) medium level robustness of the developed algorithms under new environment conditions, and specially 3) the difficulties of the know-how transfer between the developing institution and the recipient.

**SYSTEM ARCHITECTURE**

Fig. 3 presents the control system structure of the developed facade manufacturing system. Although the concept is general, for better understanding the explanation will address the specific application of manufacturing of prefabricated panels [6].

The most important aspect that characterises the system is the integration of CAD with CAM, which is indispensable to cope with small batch size production of different panels. Buildings are designed on a commercial CAD environment with access, through a special interface, to information of the manufacturing specifications and parameters and design rules of the product. The information generated by the CAD environment consists of 3D drawings and product features i.e. number and thickness of layers, etc. This raw information is processed through an off-line module, similar to computer distributed system used in [7]. There are three interrelated sub-modules form this module: CAD environment, simulation and planning. Using the information obtained
from the simulation, the planning sub-module generates commands (paths, tasks, etc.)
for the on-line equipment in the manufacturing cell: robot, computers, PLCs, etc.
The system has been designed in accordance with the flexible manufacturing concept.
The designed system’s main advantages are: direct integration of the CAD/CAM
environment, rapid design-production cycle and low-cost hardware and software
structure.
A commercial 6 DOF (Degrees of Freedom) robot was selected as the spraying machine.
A manual programming of the robot was impossible due to the complexity and the great
number of different panels. Therefore off-line programming was adopted. In this sense,
real-time communication with the robot through a computer link has been one of the key
factors during robot selection.
CAD ENVIRONMENT

One of the advantages of the system is the integration of CAD with CAM, and specially the automatic robot path-planning directly from 3D CAD designs, in a similar way to [8]. First of all the CAD operator makes a detailed design of the building which facade we want to construct. In order to facilitate the design, a series of additional software
utilities are included in the menu bar of AUTOCAD. These process-oriented utilities are dialogue boxes to guide the design process in an easy and friendly way.

**Design database**

The building design is not only the design drawing but also the components specifications. It is necessary to make a common project database in order to share the information between the different project stages and participants. The information related to common project should be grouped according to several characteristics in order to be presented in an adapted form to each participant. The building structure designed by architects is modelled in a hierarchical relation model, concretely a tree structure. This structure represents the combination of elements that go forming more and more complex components. For works programming models of nets are used, that reflect the dynamic evolution of the system more faithfully, where the most modern programming is based on Petri nets [9]. Lastly the economic analysis is carried out better using matrix models, that allow to obtain balances and to generate reports and graphics in an easy way.

Until now the change of the representation model forced the user to reintroduce all data again. In order to guarantee that the entrance of data takes place only once, we propose to establish all possible connections and attributes of the elements which belong to the object that has been defined. This project proposes some models that represent several connections and attributes of the elements, which are valid for the building construction field, but their application could be extended to the rest of the construction activities.

In the design phase we will specify a group of physical building components. Here it is considered that the most efficient handling of the information would be achieved with a tree structure like the one shown in Fig. 4. These data are generated in the design phase in accordance with the proposed outline, beginning in the top (root of the tree) where the
complete building is considered, and descending in the tree in order to detail and specify the elements that compose the entities of superior level.

In the first level we have the construction project, that is formed by a complex of buildings. Several buildings that compose the complex appear in the second level. The buildings are made up of structure, foundations, facades, interior walls, finishing, floors, electricity, plumbing, roofs, etc. These form the third level of the tree. These three levels of the tree constitute the on-site assembled and manufactured elements.

![Fig. 4 Tree structure database](image)

The building elements could be broken down into pre-fabricated products like those found in the fourth level and in half-elaborated products like those of the fifth level. The half-elaborated products could also form part of the pre-fabricated elements. In the sixth and last level we have all the basic materials that could be part of the three types of entities of the immediately superior levels: elements of the building, pre-fabricated
components and half-elaborated products. The last three levels of the tree represent the elaboration degree of the products, that are elaborated on-site or provisioned from the exterior by the suppliers which is the case of most of the materials. The subcontracting of pre-fabricated parts could also take place, very usual in the construction world.

The tree relational database proposed has the advantage that, on one hand, integrates all the components of a construction process while, on the other hand, allows to establish a clear division between on-site and external supplied elements.

**Facade restrictions**

Once the building has been drawn under solid modelling through AME, the automatic building facade generation is performed. For this purpose it is necessary to consider process specifications, i.e. maximum size of panels to be manufactured, windows and doors sectioning, etc. Finally from the elementary panels their moulds are generated.

The facade generation process is divided in four phases that are executed consecutively: extracting of the main faces of the facade, calculation of horizontal divisions, calculation of forbidden zones and calculation of vertical divisions. The process will observe a series of rules and restrictions, which are going to be explained further next.

- The moulds of the facade panels could not exceed some maximum dimensions, limited generally for the transport capacity, neither minimum, defined for constructive and design approaches according to the used material.

- The carpentry elements of the building (doors, windows, etc.) will remain included in one panel. This causes the appearance of cutting prohibited zones that coincide with the mentioned elements.

- Cuts should be located at a minimum distance from the prohibited zone borders. This is a constructive approach for problems of rigidity of the panels.
• When it is not possible to avoid cutting forbidden zones (the case of very long windows which does not fit in a single mould) the process will continue always respecting the previous rule of the margin around the borders of the forbidden zones.

• On one hand, it is necessary keep in mind the tolerances of the mould construction and, on the other hand, the panel dilatation that depends on the material used in their construction. The calculation of tolerance between panels will be carried out automatically according to the type of material dilatation.

**Facade generation from 3D building design**

Once the building has been drawn and taking into account division facade restrictions, the automatic building partitioning in the main facade surfaces is performed. Before partitioning we analyse the geometry of the facades to extract their characteristics in a similar way to [10].

In this first step we divide the facade according to their external faces. It is necessary to treat the corners in a special way, since they are considered a special constructive element of the facade. The facade corners receive different treatments according to their material and constructive solutions. Applying the solutions based on concrete techniques, the corners of the facade are built with symmetric panels respect to the common edge of two faces of the facade. This phase results in corners and main faces of the facade, as shown in Fig. 5.
Calculation of horizontal divisions

The obtaining of the horizontal cuts is based on the height and the form of the storeys. The most followed rule by designers to divide horizontally the facade is to take the intersection of each floor with the facade as division lines. This norm in most cases, like that of the Fig. 6, generates some cuts in horizontal planes.

The way of automating this phase begins in the design stage. The design should include a three-dimensional model of the building structure and a three-dimensional model of the facade. Inside the model of the structure the elements which compose the divisions between storeys must be identified. Later on, the intersection of elements with the facade is calculated and a cut line is chosen in the feasible range, for example in Fig. 7 the chosen cut lines appear drawn in a discontinuous line. The definition of the storeys
by means of their cut lines is the information that will be used as starting point in the next phase.

![Fig. 6 Horizontal facade division](image)

**Determination of the cut forbidden zones.**

As explained previously, the facade divisions can not cut forbidden zones, which are defined by elements like windows, doors, holes, etc. Furthermore this zones should be completely included inside one panel if it is possible. After the division of the facade in floors the forbidden cutting zones are automatically identified for each floor. Next, the designer could mark new additionally forbidden zones, due to aesthetic or rigidity reasons.

The first step in order to calculate the forbidden zones is the calculation of the elements that are physically in the facade. To do this the XY plane of the reference system is
made coincide with the main plane of the facade and the Z-axis is taking pointing outside of the building. Once our reference system is located each floor is cut by a set of ZX parallel planes. These planes are evenly distributed on the Y-axis interval occupied by each floor, see Fig. 7.

Then the sections obtained by means of the cuts in XZ planes are analysed, see Fig. 8. At this point all discontinuities that appear in these sections are considered as forbidden zones.
There is a series of special cases, which could be encountered and are summarise in:

- **Very small holes**: if they were between two cutting planes, they would not appear reflected like forbidden zones. The solution is to adjust the distance between cutting planes according to the size of the holes. Another option is to increase the size of small holes up to the distance between cutting planes.

- **Non rectangular windows** (Fig. 9 to the left): the results are different intervals for the same window, this situation is solved considering as forbidden zone the widest interval along X-axis that embraces the whole window.

  ![Fig. 9 Non rectangular windows and coincident windows](image)

- **Coincident windows**: applying the previous approach to windows with any common interval, like those of Fig. 9 to the right, the obtained effect is to reduce the number of considered windows. This is a good solution because the overlapped forbidden intervals are jointed in a single one.

**Calculation of vertical divisions**

In this step, the final facade division is calculated satisfying the specifications of maximum size of the mould and does not cut the forbidden zones.

Algorithms have been developed according to three partition approaches:

- **To minimise the total number of panels in the facade**: this criterion minimises the times of transport and panels assembly. The problem is that we obtain non-uniform
facades because it is easy that vertical divisions of consecutive floors do not coincide, and the process may generate some very small panels.

- To minimise the number of moulds: this criterion minimises the panels production time. It gives us a more uniform solution but we obtain facades with a high number of vertical divisions.
- Mixed: to minimise the total number of panels trying to obtain the highest number of equal moulds. This algorithm gathers the advantages of the previous two avoiding their inconveniences. Vertical divisions in consecutive storeys tend to be more uniform, the panels tend to be quite big and the appearance of very small panels is scarce.

 Algorithms to minimise the number of panels

These algorithms have the objective to obtain panels with the biggest possible size, but with dimensions, which are not very disparate. This means that it tries to avoid having some big panels and several panels significantly smaller. The basic method to minimise the number of panels, which is the starting point of all the algorithms and developed originally in this work, consists of the following procedure:

Analysing each floor individually; it starts at the extreme left of the floor and it tries to put the division to the maxim possible distance. This means that it tries to obtain panels with the maximum length defined for the material to use in their manufacturing, as long as the division do not coincide whit a forbidden zone.

In case the division falls inside a forbidden zone, the valid cut will be the one that it is in a permitted zone the longest possible. This way we proceed until arriving at the right end of the floor facade, taking the valid previous division as the beginning point for the following. This procedure is illustrated in Fig. 10.
So far, we have obtained the division in one direction. In the figures invalid cuts have been drawn in discontinuous line and valid ones in thick lines. Afterwards, the same steps are executed starting from the right end of the facade and finishing at the left end, as shown in Fig. 11.

Once these two series of divisions are calculated, the following step is to obtain the final cuts by means of the following procedure: the order of one of the series is inverted and the middle of each couple of divisions is calculated. These are considered as an acceptable provisional results. However it could happen that one of these divisions fall inside a forbidden zone. In this case, the invalid cut will be moved to the limit of the forbidden zone until it becomes valid.

If no valid solution is obtained, because a panel is bigger than maximum size, the solution consists of two divisions instead of one. These are the ends of the analysed interval, which had been obtained as valid divisions upon calculating the two series of cuts. All this procedure is illustrated in the Fig.12. Definitive vertical divisions appear in thicker lines.
Fig. 12 Definitive solution for a floor

The advantage of this algorithm is that it tends to obtain panels as big as possible. The disadvantage is that it does not try to obtain panels exactly equal, neither it tries to cut in the same places in consecutive storeys. It might also obtain very small panels in conflictive zones.

Algorithms to minimise the number of moulds

To avoid the disadvantages of the previous algorithm it is necessary to consider the set of storeys’ facades, jointly. The first approach to a solution is to apply the previous algorithm to the whole main face of the facade. Before proceeding, we have to join forbidden zones in all storeys and consider the main face as a single storey, and therefore the vertical divisions obtained by this way are valid for all storeys.

The problem is that if the facade is not uniform there could be no solution for the whole building, as illustrated in Fig. 13; there is no global solution.
Mixed algorithm to minimise the number of moulds obtaining big panels

The final algorithm constructs fictitious floors with several consecutive real floors. Consecutive floors, which are very similar, are grouped in a set joining their forbidden zones. Then we apply the basic algorithm to the fictitious floor obtaining a global solution for each set. In Fig. 14 we can see the solution dividing the facade into two sets of floors: the ground and the other two floors. The solution divides the facade into ten panels that can be manufactured with six moulds.
The outline of the whole process of vertical divisions calculation is shown in figure 15:

![Diagram](attachment:image.png)

**Fig. 15 Method to minimise the number of panels**

### Generation of the three-dimensional model of the panel

The results of the previous phases are a list of horizontal divisions for each main face and a list of vertical ones for each floor. The following procedures work with boolean operations with three-dimensional solids. With the list of horizontal divisions the solid of the main face is divided into floors, as can be seen in Fig. 16. The figure shows the floors separated for better clarity of the drawing.
With the list of vertical divisions each floor is divided into the solids that constitute it. Fig. 17 shows a facade divided into all the panels that compose it. Each panel is stored as a three-dimensional independent object for further treatment in posterior stages.

Fig. 16 Main face divided in floors

Fig. 17 Three dimensional solids of facade panels
**Generation of the three-dimensional model of the mould**

Once we have the "positive", or the panel that we want to manufacture, it is necessary to obtain the "negative", the mould on which the panel is manufactured. The operation consists of subtracting the solid of the panel from a box solid object that encompasses it with certain margins around it. This way we obtain a box with a hole in its interior, which is the panel.

Previously, we put some lateral faces to the panel in the adjacent zones to the neighbouring panels. These joints are the sealing zones between panels. These lateral faces should have enough height so, that once subtracted together with the panel, the solid box results divided in two solids. The selected solid is the one that is in contact with the external face of the facade, like the sample shown in Fig. 18.

Additionally, it is necessary to keep in mind the construction tolerances. It is necessary to design the union joints between panels with an appropriate width in order to absorb errors inside the margin of foreseen tolerances, the possible dilatations of the panels and to seal the unions with silicon gum.
Placement of auxiliary elements in the mould

The mould should include some necessary elements such as: the extraction devices of the panel, the manipulation and support anchors, etc. These elements are put together in a library of standard pieces, which one could handle dynamically adding or modifying them.

Fig. 19 shows the AutoCAD interface where all described processes are executed from.
PLANNING OF THE ON-SITE ASSEMBLY

Once the facade panels of the building are obtained, it is necessary to plan their transport and assembly on-site, see Fig. 20. The architectural design of the building can also be used as starting point for the on-site assembly planning of the pre-fabricated elements. This planning consider the rhythm of the on-site works and the resources available for the assembly operations.

Fig. 20 Planning to assemble pre-fabricated parts
ON-LINE MANUFACTURING MODULE

The automation of the panels production is performed using the automatic generation of all the trajectories and tasks’ sequences of manufacturing [11]. This generation uses the three-dimensional solid model of each mould obtained in the previous stage as input information [12]. This process goes through of several stages that could summarised in:

a) Generation of manufacturing tasks

For each panel, the operator must specify various general process and tool parameters, which normally remain fixed for several panels. Finally, the operator can launch the automatic process generation in the CAD environment.

   Spraying rules: task path planning process depends mainly on some spraying rules that were obtained from a careful study of manual spraying.

b) Robot path planning

There are several steps in the automatic robot path-planning algorithm. This algorithm receives data of the 3D mould drawing together with the spraying parameters, and it generates the real robot path and manufacturing commands (Fig. 21).

   b.1) Robot path generation. The path planning algorithm works in first place with a spraying path only and then transforms it to a robot path [13]. From the mould data (Fig. 21a) a theoretical spraying gun path (Fig. 21b) and a real spraying path (Fig. 21c) are calculated.
b.2) Kinematics robot path. The objective is to position the robot with the appropriate theoretical orientation over the panel (Fig. 21d). Following, the robot kinematics is analysed for the first time generating the adapted robot path (Fig. 21e).

b.3) Robot approach and retreat. The final step in the path planning is the generation of a real robot path (Fig. 21f) through the use of robot approach and retreat algorithms.

c) On-line control of the robot cell

The manufacturing of a GRC panel goes through several stages: 1) mould preparation (including the placement of clamps for later assembly on site), 2) spraying/compacting, 3) hardening, 4) panel extraction from the mould, and 5) curing.
c.1) System Architecture. Fig. 22 shows a scheme of the cell. The main elements are: spraying robot, spraying gun, on-line main computer, off-line computer, Programmable Logic Computers (PLCs) and roller conveyor.

Fig. 22 Scheme of the cell

c.2) User interface. Fig. 23 shows the man-machine interface during on-line control of the cell. Different user friendly menus allow the interaction with the cell.
EVALUATION STUDY

To evaluate the achieved improvements the developed automatic panel design system is compared to traditional design. The comparative study is based on two key factors: product life cycle time and overall productivity [14]. The panel manufacturing time cycle can be divided into two different phases: a) mould design and drawing followed by path planning, and b) manufacturing in factory. The first phase, which is performed completely off-line, can be done in the technical office.

The life cycle to construct building facade with prefabricated parts is formed by two different phases: off-site operations and on-site assembly. Firstly we have automated the off-site operations which are:

- Building design, that is the input for next automated processes
- Facade design
- Establishing facade specifications
- Facade division in parts
- Production and assembly planning
- Automatic generation of tasks to manufacture facade parts
- Graphic simulation of manufacturing operations

The process is very similar to manufacture special parts, in this case we design the part and then we obtain the mould to manufacture it. When we have the panel the process is the same as the one described previously for panels obtained from the automated process.

<table>
<thead>
<tr>
<th><strong>OFF-LINE PROCESSES</strong></th>
<th><strong>Time (min.)</strong></th>
</tr>
</thead>
<tbody>
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<td><strong>Marcador no definido.</strong></td>
<td>**Manual</td>
</tr>
<tr>
<td>Facade design</td>
<td>180</td>
</tr>
<tr>
<td>Facade division</td>
<td>30</td>
</tr>
<tr>
<td>Manual modifications of facade division</td>
<td>40</td>
</tr>
<tr>
<td>Panel and mould generation</td>
<td>90</td>
</tr>
<tr>
<td>Tasks generation</td>
<td>150</td>
</tr>
<tr>
<td>Manual modification of tasks</td>
<td>60</td>
</tr>
<tr>
<td>Production planning</td>
<td>20</td>
</tr>
<tr>
<td><strong>Total time</strong></td>
<td>62</td>
</tr>
</tbody>
</table>

Table 1 Off-line operations times

Despite of the several advantages of the proposed automatic design and manufacturing system, it is necessary to stress one of the most important contribution of this work, which is the implementation of the CIC concept making easy access and sharing
information. Some of the operations were already done in a more or less efficient way, but the necessary integration of the information did not exist.

Regarding the off-line works the analysis of the productivity leads to analysing the execution times of each operation. Table 1 presents estimation times for each phase. The facade design is carried out having as input data the building design. The A option represents the required time in order to generate a new facade from a building design. The B option represents the required time in order to modify the division of a previously calculated facade. Finally the C option represents the required time in order to adjust the production parameters and generate new tasks.

CONCLUSIONS

The developed system (Fig. 24) presents a new step towards fully automatic prefabricated manufacturing. The development of this system has shown some of the great advantages that automation can bring into quality and productivity in an off-site manufacturing process of construction.

Toda la arquitectura software se ha montado para la empresa constructora española Dragados sobre AutoCAD Version 14, donde se han programado todos los algoritmos de división de fachadas que se han desarrollado mediante programación orientada a objetos utilizando Visual C++ Version 6.

Con la ayuda del entorno CAD se estan fabricando paneles de todo tipo, partiendo del diseño CAD 3D del edificio. Se han mejorado sustancialmente los tiempos de ciclo desde que se entregan los planos del edificio hasta que comienza la fabricación de los paneles de la fachada. La oficina técnica y las bases de datos residen en la sede central de la compañía, que estan conectadas con las fabricas que reciben las ordenes y programas de fabricación.
This research project has had a total duration of more than two and a half years. It proves that new robotic technologies can be introduced in construction industry with good results. The research done during this time has also contributed to a better understanding of the production process and to search for new ways of automation.

Fig. 24 developed system

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