Publishable Summary

The recognition that increasing the re-use of mixed post-consumer plastics waste is an excellent opportunity to reduce the impact of high raw material prices. It will also significantly reduce the cost burden of EU WEEE and Waste Directives and help reduce Europe's growing plastics waste problem. The reuse of mixed waste plastics is appropriate for low to medium value products such as building materials, flood barriers, temporary structures, flooring and marine products. This is also the main market segment that is losing out to non-EU competition. Enabling this segment to reduce materials costs will lower demand for virgin polymers (and potentially other materials such as plywood and metals), which will have a downward effect on raw material prices. Simultaneously, the increased demand for recyclate will help the polymer recycling industry.

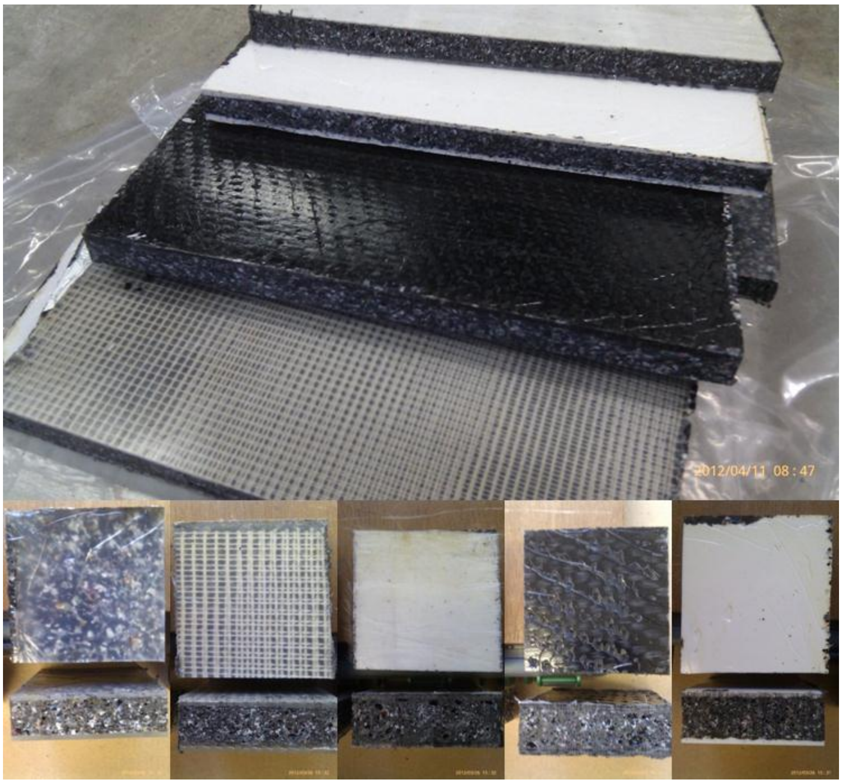
In the PRIME project we propose to develop a cost-effective, flexible moulding technology to manufacture high value, complex, recycled polymer products (80-98% mixed waste polymers) with similar or identical mechanical properties to virgin polymer, metal or timber alternatives. The process must be suitable for a wide range of complex products such as flood barriers, temporary walkways, emergency structures and buildings, and marine products.

The PRIME (Plastic Recyclate Impression Moulding Engineering) process is aimed to produce sandwich panels of two outer layers (referred to as skins) and a core. The boards were 1000x500x20mm with skins of various thicknesses (2 and 4mm).

Trials of methods to apply polymer skin in the form of a film were done. However trials using the polyolefin film and trying to manufacture desired shapes were carried out however the films were too flexible thus presenting various difficulties and this work was suspended. Plastic films are normally less than 0.5 mm. thick which is too flexible for our PRIME processing technology therefore multi layers of films need to be laminated to make up the necessary 2mm thickness for PRIME application which makes the process too complicated, energy hungry and expensive. It was decided that instead of using thin and soft films, the thicker and more rigid sheeting was chosen to form different skins for evaluation using different forming technologies.

For the core the majority of the raw materials were received as flakes or pellets, and these were size reduced. Different combinations of recycled Polyolefin (PO) and Polystyrene (PS) were trialled and a mixture was chosen as the core material. A number of sample sandwich boards were manufactured using the chosen core material and different skin formulations. The skins were manufactured using different forming.

The boards were then made by laying a bottom skin in the mould, filling it with the pre blended core and then laying a top skin on the core. For simplicity these were manufactured using compression moulding, see figure 1.



Figures 1: Manufactured sandwich board samples

Both skin sheets and PRIME boards were tested by using a drop weight impact tester followed by optical examination and were carried out in accordance with ISO 6603.The fractured surfaces and section from the impact tests were examined optically (see figure 2). Images can determine the different morphology of fracture propagation of skin and core.

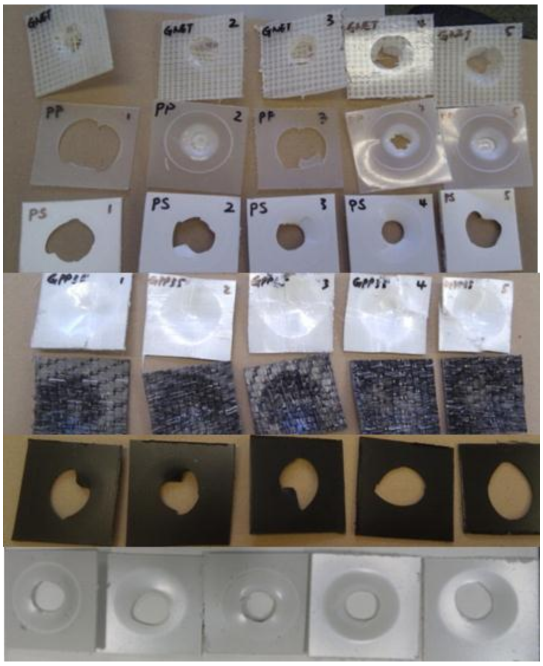


Figure 2: Images of skin samples subjected to drop weight impact tests.

The test results are summarized in Figure 3 with a couple of skins showing promising results.

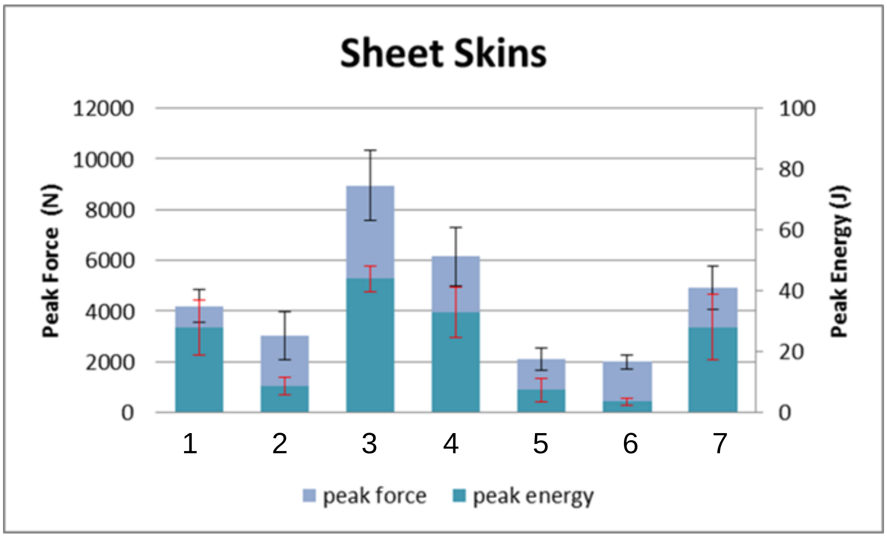


Figure 3: Results of the impact tests on different skin formulations

Chip wood board samples and a plywood board samples (Figure 4) with similar thickness of PRIME boards were also tested for comparison purposes.

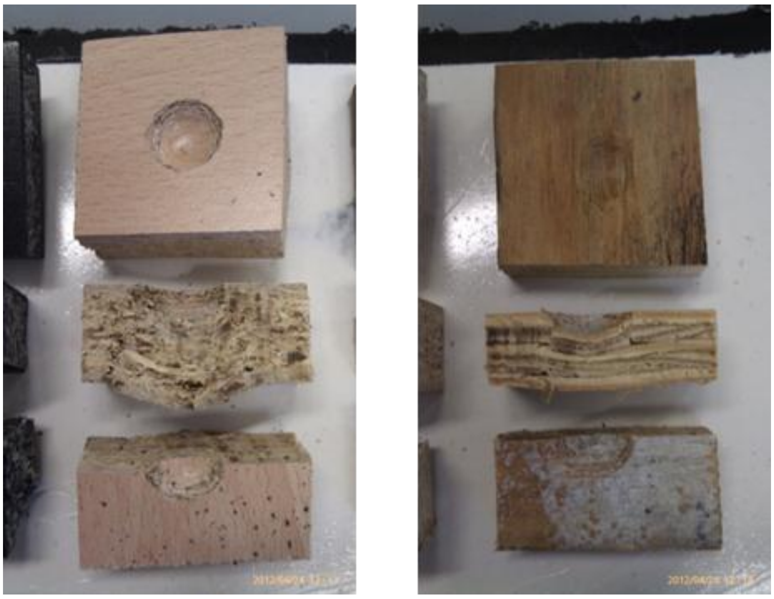


Figure 4: Image of wood samples subjected to drop weight impact test.

Test results of flat PRIME panel are summarized in Figure 5 along with plywood boards.

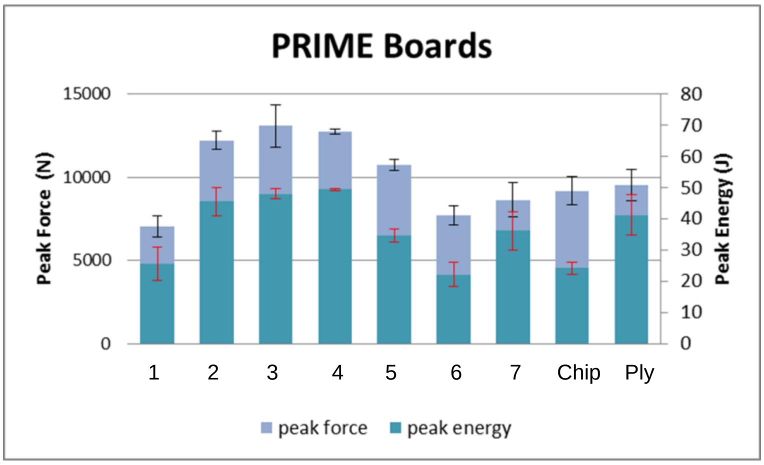


Figure 5: Results of the impact tests on PRIME boards and plywood boards

The overall conclusion is that the choice of skin materials plays a major role on the PRIME products. It is also encouraging to report that our work and tests are demonstrating that the developed PRIME products display similar if not superior level of properties when compared with plywood.

A basic heating model was developed in Period 1for estimation of process times and energy requirements based on a generic conductive heating process. The configuration of mould, skin and core considered in the model is shown in Figure 6

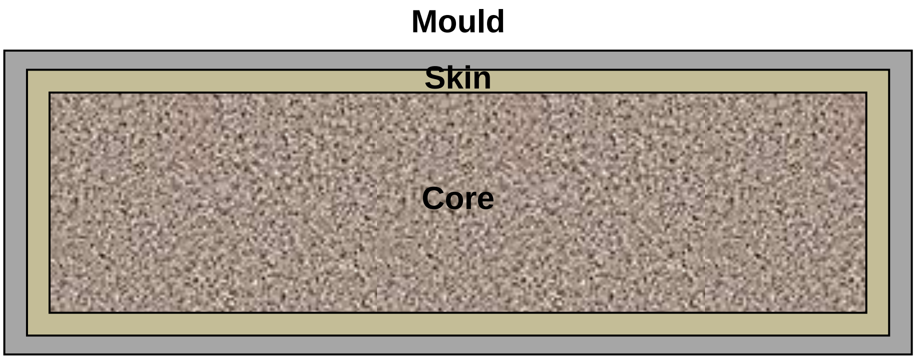


Figure 6 - Geometry considered for PRIME modelling

The materials assumed for the components are listed in Table 1 along with the relevant physical properties**.**

Part	**Material**	**Density (kg/m3)**	**Specific Heat Capacity (J/kgK)**	**Thermal Conductivity (W/mK)**
Mould	Aluminium	2500	900	250
Skin	Polypropylene	950	2000	0.15
Core	Polystyrene	1000	1170	0.1

Table 1 - Model components and material properties

Table 2 lists the assumed dimensions for each of these parts. The most important parameters in terms of time and energy requirements are panel area and core thickness. The effect of these parameters is studied by considering a wide range of values for each of them.

Parameter	**Typical Value/ Range**
Mould Thickness	10mm
Skin Thickness	5mm
Core Thickness	10-100mm
Panel Area	0.1-2m^2

Mould Temperature	230°C

Table 2 - Dimensions of model

In order to keep the model simple to analyse and understand, the following assumptions have been made:

- Heating of the skin and core is assumed to be a conductive process. This is physically accurate for the present case as conductive heating will be far more significant than convection or radiation.
- The mechanism of heating the mould is not considered in the present model. This can be included post-modelling as an efficiency factor.
- Losses to the atmosphere are neglected as the losses will be highly dependent on the actual heating mechanism.

A Microsoft Excel model was prepared for estimating energy and time requirements based on the previously described model.

For a given core thickness, the energy requirement increases linearly as the panel area is increased, Figure 7, due to the increased masses that need to be heated. However, the time required is essentially constant since the heat flux is independent of panel area. The small reduction in the time required is due to the variation in relative proportion of core and skin with changes in panel area. This variation in relative proportion of core and skin leads to a change in the overall thermal conductivity due to the different material properties.

With the panel area fixed, the energy requirement again increases linearly with increase in core thickness, Figure 8. However, the time required increases exponentially due to the reduced heat flux with increased thickness.

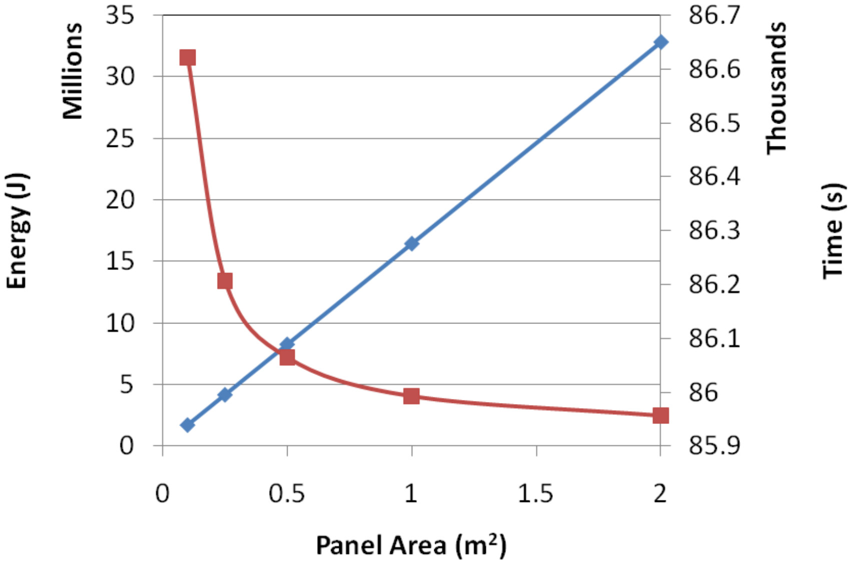


Figure 7: Energy and time requirements for a panel with core thickness = 50mm and skin thickness = 5mm.

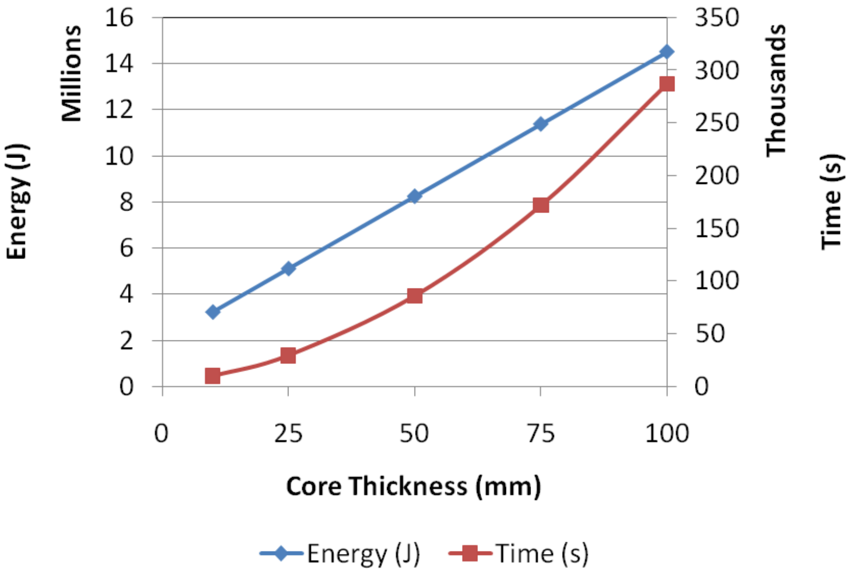


Figure 8: Energy and time requirements for a panel with panel area = 0.5m2 and skin thickness = 5mm.

The simple model considered does allow us to make a few important observations:

- Energy required increases linearly with panel area and core thickness.
- Time required is essentially constant with panel area but increases (approximately) quadratically with core thickness.

Following positive development of IR trials in Period 1, a rig was developed by Caro FDS to house the two IR heating system. The rig was designed to be flexible in allowing assessment of the following;

a. Effect of distance between the IR heating and mould surface.
b. Effect of cooling of the different distances between the IR heater and mould surface
c. Effect of time on the heating profile in the mould tool

The spectral power density of the gas catalytic burner can also be configured by altering the gas/air ratio. This allow the burner to operate in either the red flame (620–750 nm wavelength) which give efficient heating to the part or blue flame mode (450–475 nm wavelength) which concentres most of the heating on the air gap between the burner and the part, thus by changing from one mode to the other it is possible to efficiently configure the heating cycle of the process.

From the trials carried out the red flame option was chosen, as can be seen in Figure 9, the IR heater rig. This gives an output between 3Kw to 10Mw with a burner surface temperature up to 1000°C.

Figure 9: IR heater rig

Small moulds both metal and ceramic were coated with sprayable conductive ceramic materials using an automated process. Figure 10 shows the cross section of what happens within the spray gun.

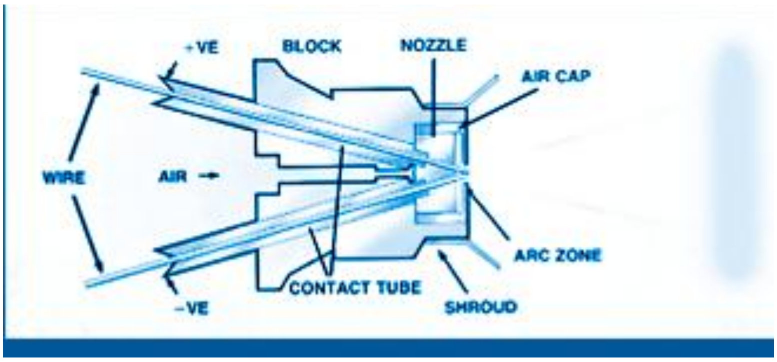


Figure 10: Spray gun process diagram

The spray gun was fixed to a sliding mounting bracket. This allowed the gun to be move around the work piece. This allows the distance to be altered depending on spray effect. The Arc spray system is operated in a fume cupboard using remote control devices for the XY table and Spray unit see figure 11.

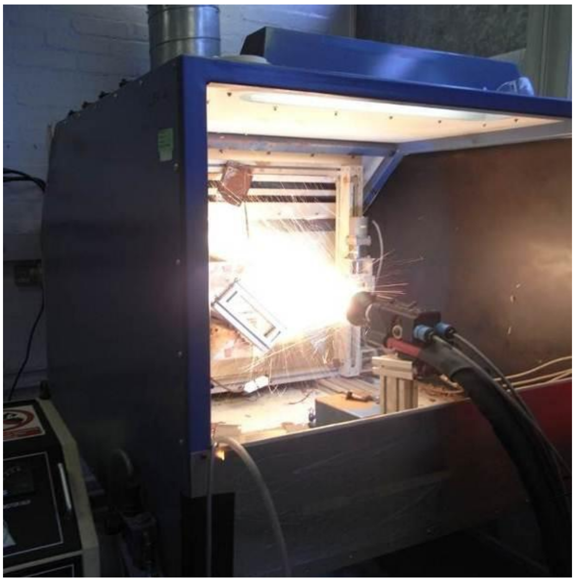


Figure 11: Testing of sprayer

Figure 12 shows the element produced. The thermal image shows a thermal spread across the element. It is noticeable however that there is a hotter central section.

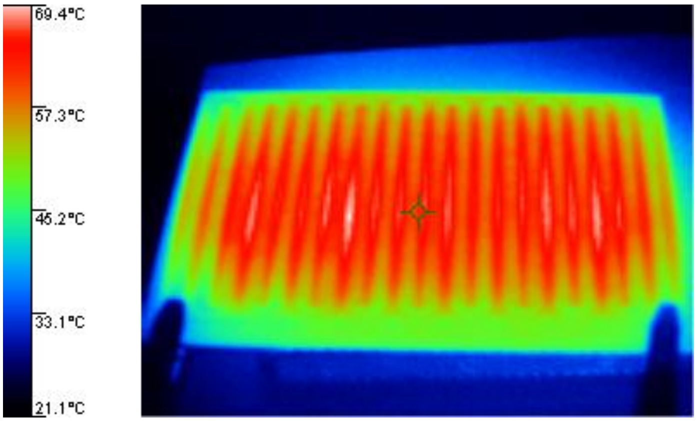


Figure 12: Infrared Image of the Heater produced

In conclusion, a ceramic element system has been produced and trialled, however it is was considered that at this time in the project the gas catalytic heater was the best option.

In order to obtain the optimum mould heating methodology, calibration trials were carried out. A thermocouple attached to a temperature data logger was inserted into the mould tool. The data extracted from the data logger was then plotted to show the temperature profile of the different distances between the IR heater and mould surface.

Figure 13 shows a steady and controlled increase in temperature.

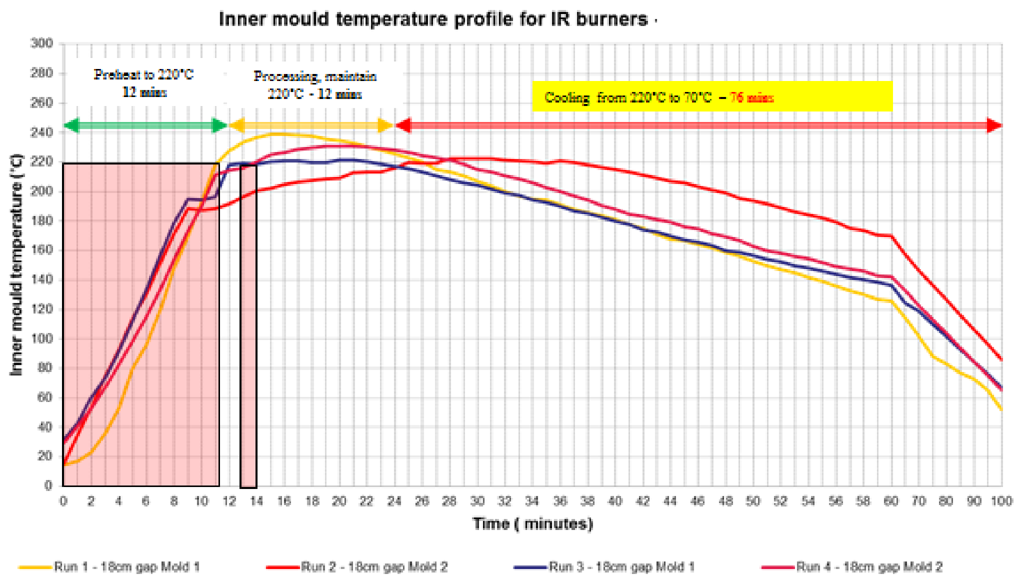


Figure 13: Temperature profile for 18cm gap between IR heater and mould surface

Following calibration trials, more than 32 different products, as shown in Figure 14, were manufactured and were made from different combinations of skin and core materials

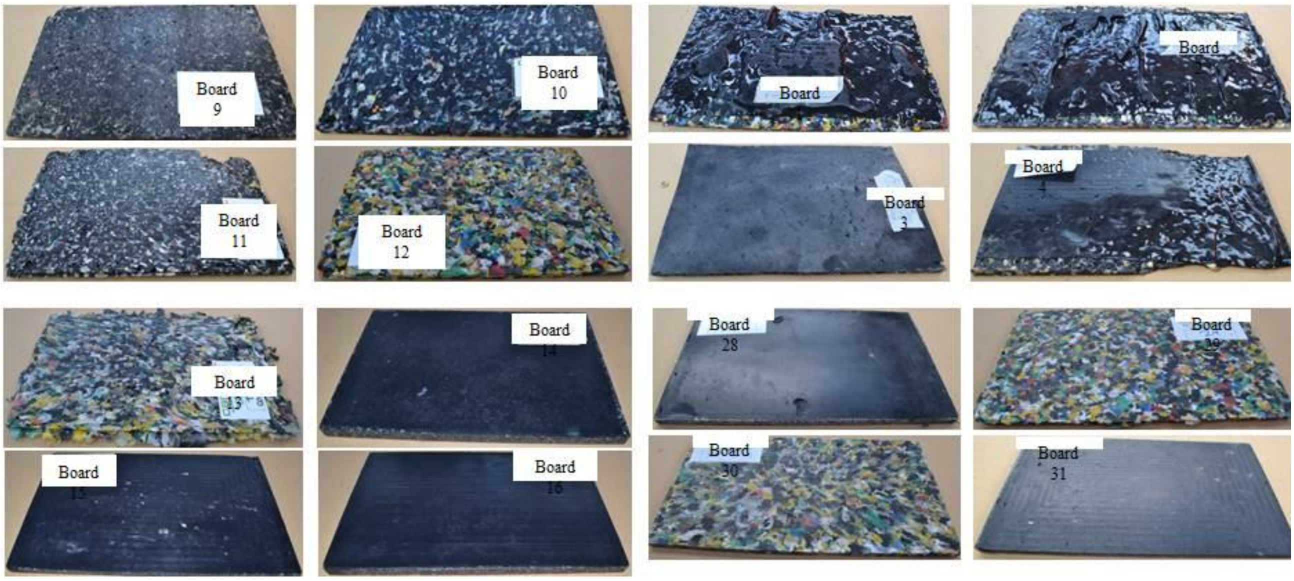


Figure 14: Examples of products made from IR heating

The products made were instrumental in helping the Consortium understand the effect of the different material and process variables. The processing parameters and material constituents have been identified and will be tested for repeatability trials in trials being carried out in Period 3. In conclusion the IR heating system has been proved to be able to consistently produce products in a 20 minute heating cycle. The system is cost effective, safe and economical to use. The prototype system is now being produced for evaluation in Period 3

Modelling of the PRIME beam, using standard beam theory and corresponding analytical formulas was carried out and this work led to the development of a design tool able to quickly provide quantitative data on the performance of the PRIME composite panels submitted to simple loading conditions. Interesting results are the mechanical response of the panels and the strength of their materials (Figure 15).

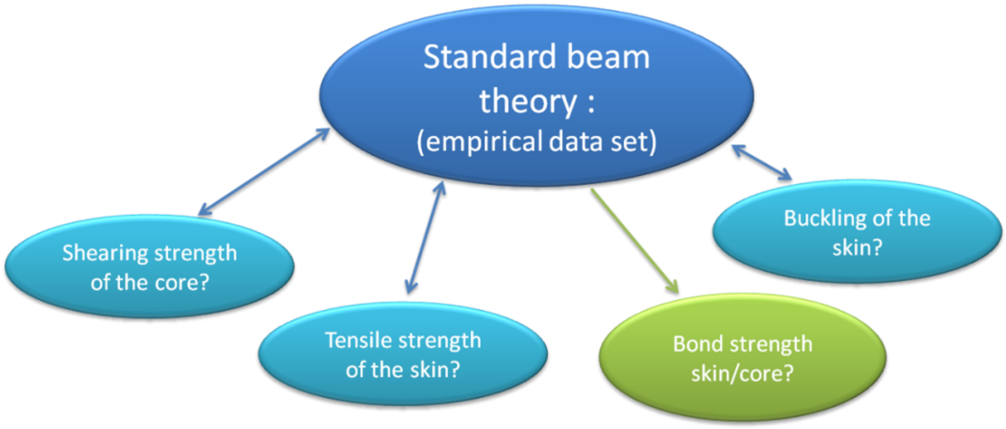


Figure 15: Outline of the standard beam theory

The geometry defined by the consortium was for a composite sandwich panel made of a core flanked by two sheets of dense polymer (i.e., the skins). As an approximation, boundary conditions were defined using the loading resultant which can be evaluated by the pressure distribution on the panel. Secondly to ensure the assumption of a 2D resolution, the load is uniformly distributed on a side of the panel and the panel is pin jointed at each end (Figure 16).

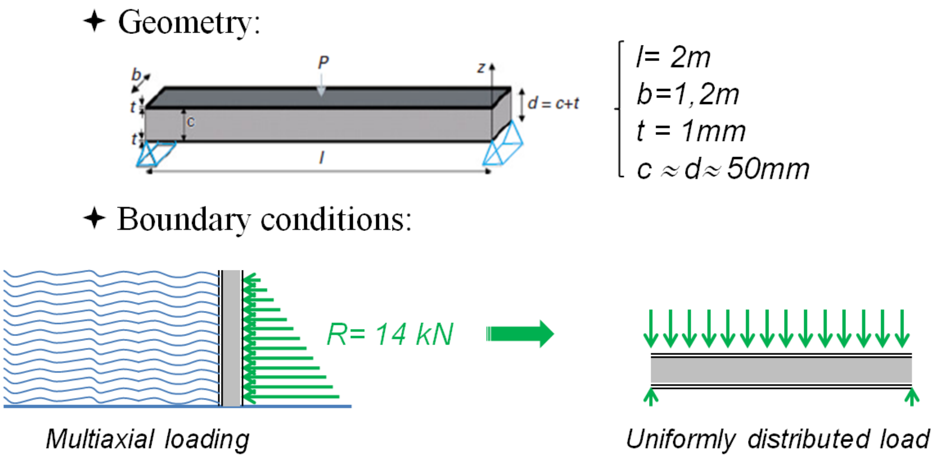


Figure 16: Simplified analytical model of a PRIME beam

The analytical model of the PRIME beam was implemented in Microsoft Excel solver. A corresponding spreadsheet was produced for allowing the user to easily enter the design parameters values. Depending on the water height (equal to the height of the panel), the software calculates the equivalent load applied to the panel. For this analytical calculation based on the beam theory, the assumption of uniformly distributed load was applied (Figure 17).

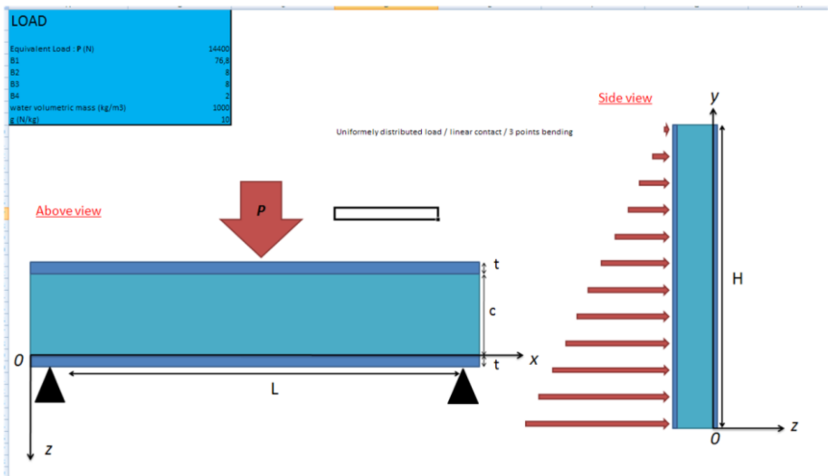


Figure 17: Excerpt of the Excel spreadsheet produced (loads modelling)

A computation of the relative deflection of the beam (defined as the maximum transverse displacement divided by the beam length) was implemented. According to the Consortium, this ratio should not exceed 2%. By comparing the stiffness of the composite beam to the one of a beam with homogeneous cross-section and the same outer dimensions, it is possible to calculate the “equivalent Young’s modulus” of the composite beam. This was implemented in the solver. Moreover, an inverse resolution was proposed too. It allows estimating the properties of the skins (stiffness and thickness) which lead to a given equivalent Young’s modulus of the composite.

An analytical tool was developed in order to assess the mechanical response of very simple geometries and loadings. It has been validated with successive Finite Element 3D models. Indeed, FE models allow solving more complex situations and more realistic designs: realistic boundary conditions, structural effects, non-uniform loadings, triaxial stresses state. Finally, these models led to develop the computational basis and build a validation tool (Figure 18).

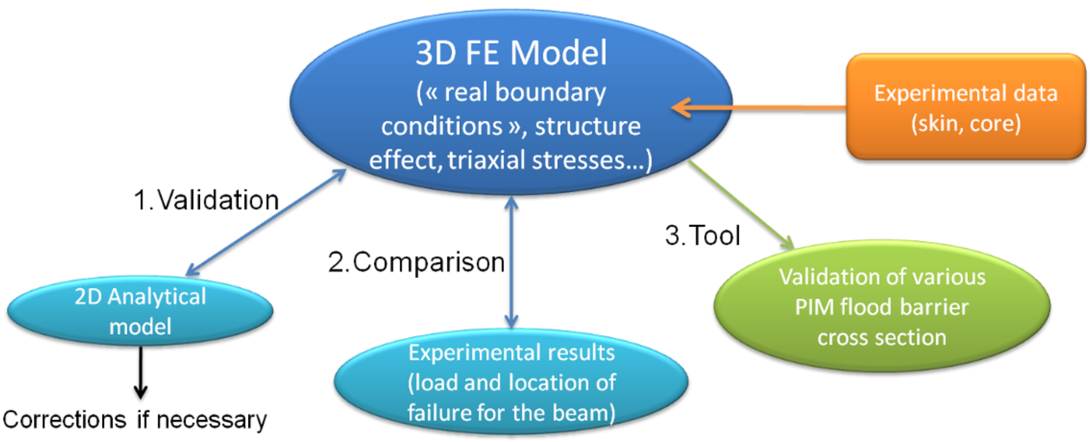


Figure 18: The computational models and the validation tool

Then, many shapes and designs were studied for PRIME panels. This was necessary to mature the choice of a “good” composite design, according to the FE modelling capabilities. Corresponding FE models were built, analyses were conducted and we focused on two mechanical values: the maximum bending stress and the relative deflection of the panel.

Though a rather simple global shape was retained, there are various possibilities to design the curved panels, which must cope with numerous parameters: dimensions, thicknesses, shape, boundary conditions, and different types of loadings (Figure 19)

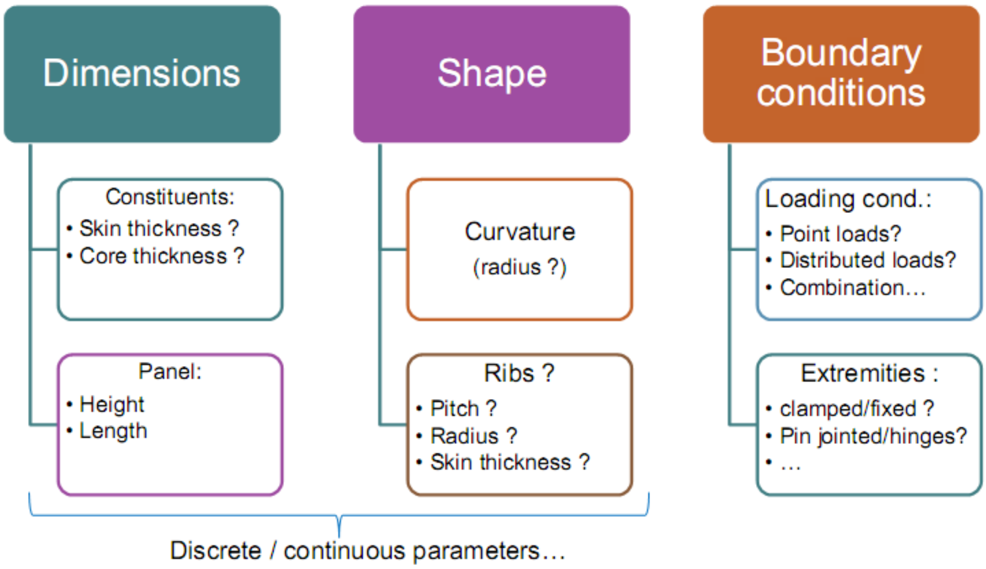


Figure 19: List of possible design parameters

Different load cases were modelled: uniform pressure, hydrostatic pressure, point force and line force (Figure 20), each with variable magnitudes.

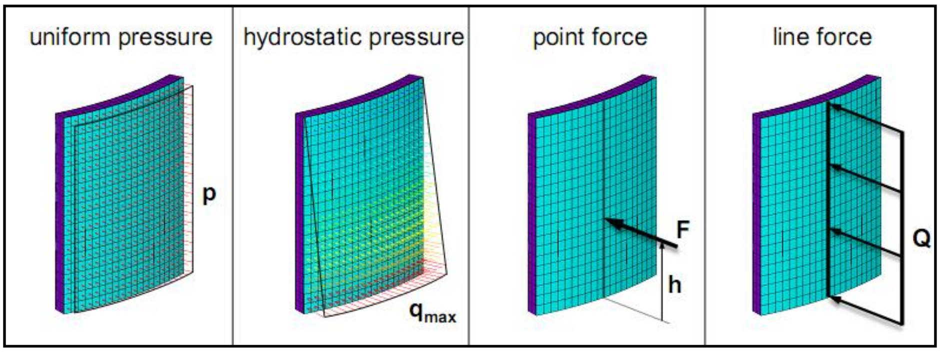


Figure 20: Different load cases

The conclusions were that the variations of the length or the global thickness have a strong effect on the maximum bending stress of the panel. The height had no significant effect (for this load case). Material properties have moderate effects on bending stress (for this load case). Curved panels are stronger than flat panels, due to the compression effect. It is important to note that the main problem could be the poor distribution of reinforcement within skin elements. For a given dimension, materials, and load case, curvature led to increase the stiffness and the strength of the panels; however, flat panels were the preferred option.

A Finite Elements results database was built, for scattered values of the design parameters in the possible range of each parameter. The FE database includes four loading cases. Four partial databases make up the whole database. The four loading cases (i.e. the four partial databases) are:

- Uniform pressure
- Hydrostatic pressure
- Point force
- Line force

For every loading case, 78125 values were computed (i.e., the combination of seven variables with five values each). So, solving the whole database involved 312500 FEA and took almost one week of calculations using a powerful PC.

Numerical post processing routines were developed and included in the design tool software. These routines are based on the data fitting of the FE results. For that, two different strategies were considered: a global or a local data fitting.

Firstly, global data fitting was tried but didn't yield good results. It is due to the complex situation of a n-dimensions data fitting (n = number of design parameters), which makes it difficult to find a relevant global interpolation function.

A multivariate local data fitting strategy has been implemented inside the design tool. It allows computing the mechanical results for any selected values, by exploiting the surrounding results of the FE database which can be considered as a grid of "exact" values.

The implemented interpolation is based on successive linear interpolations. Hence, a multi-dimensional problem was decomposed into a succession of simpler mono-dimensional problems.

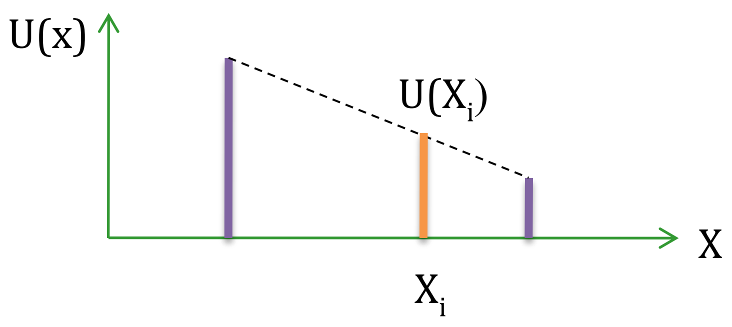


Figure 21: 1D linear interpolation

The principle of 1D interpolation is shown in the Figure 21. $U(X_1)$ and $U(X_2)$ are results of FE evaluation (i.e. exact values). They are values from the database. X_1 and X_2 are two closest sampling values around the objective value X_i. Classically, $U(X_i)$ is obtained as follows:

$$u(x_i) = u(x_1)\left(\frac{x_2 - x}{x_2 - x_1}\right) + u(x_2)\left(\frac{x - x_1}{x_2 - x_1}\right)$$

This method is a local linear interpolation.

The knowledge and the computation techniques that were developed led to a user-friendly interface (Figure 22). The design tool interface gathers all the necessary information: numerical inputs, a link with the materials data, and several checkboxes to select or add different load cases.

The software uses a "traffic signal" style indicator. Green, yellow and red colours mean respectively that both, one or none of the mechanical conditions have been satisfied. The computation for a set of parameters takes only a few seconds to solve.

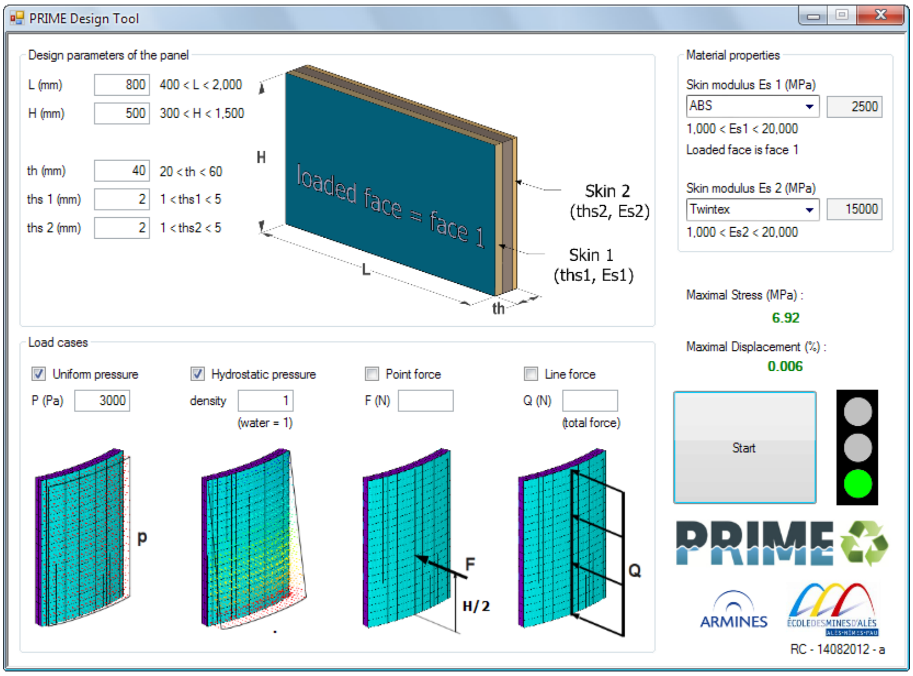


Figure 22: Screenshot of the PRIME Design Tool interface

In order to design the integrated mould a stress/strain modelling based on finite element analysis was carried out to predict the deformation of the mould under a load due to foaming pressure inside the mould. The conclusion from this study is that modelled support design (Fig 23) using I beams keeps the aluminium mould deformation below the tolerance level with a maximal deformation achieving approx. 1 mm under 150 KPA

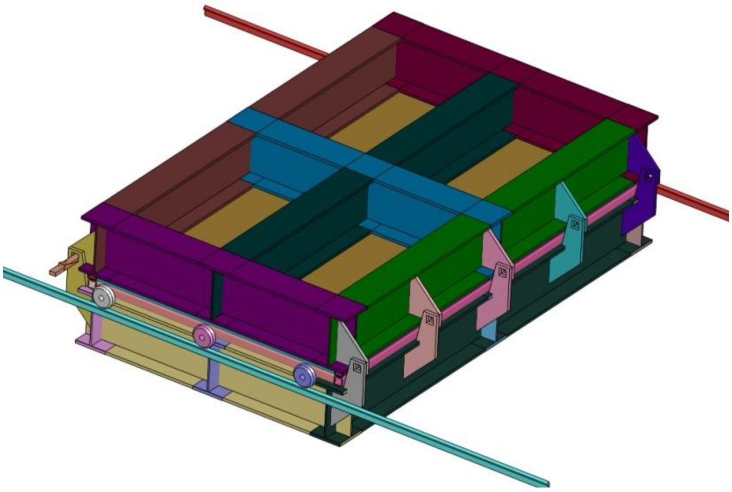


Figure 23: Theoretical Mould design

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