D4.5 REPORT ON THE RESULTS OF THE TESTING AND VALIDATION STUDIES

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October 2019
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**THE CoPro PROJECT**

The goal of CoPro is to develop and to demonstrate methods and tools for process monitoring and optimal dynamic planning, scheduling and control of plants, industrial sites and clusters under dynamic market conditions. CoPro pays special attention to the role of operators and managers in plant-wide control solutions and to the deployment of advanced solutions in industrial sites with a heterogeneous IT environment. As the effort required for the development and maintenance of accurate plant models is the bottleneck for the development and long-term operation of advanced control and scheduling solutions, CoPro will develop methods for efficient modelling and for model quality monitoring and model adaption.

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Abstract

WP4 focuses on the development of models, solution algorithms and methodologies for complex industrial facilities including both batch and continuous processes. All developments have been inspired by the P&G and FRINSA industrial problems. Both companies provided all the necessary data to CERTH and TUDO to test efficient solution approaches and perform extensive validation studies described in this Deliverable. More specifically, MILP-based decomposition algorithms have been investigated for large industrial problem instances. Several validation studies have been made in order to assess the applicability and efficiency of the proposed models, algorithms and methodologies. All validation studies reveal that the optimisation-based scheduling approaches result to good quality schedules with significant benefits in terms of changeover and makespan minimisation. More specifically, several tests, related both to the fixed and agile plant layout revealed that the generated schedules fully satisfy all plant operating and design constraints and lead to significant improvements in terms of changeover and makespan minimisation. Furthermore, two representative case studies related to the FRINSA use case have been solved, using realistic data. The derived schedules satisfy all operational and technical constraints and result to significant changeover minimisation. It has been concluded that the proposed mathematical frameworks developed in Tasks 4.1 and 4.2 can be successfully applied to large-scale industrial problem instances considering both makespan and total changeover time minimisation. All results lead to near optimal scheduling solutions in reasonable computation times.
**Revision History**

The following table describes the main changes done in the document since it was created.

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<td>V0.1</td>
<td>7 October 2019</td>
<td>Document created</td>
<td>A. Elekidis (CERTH), G. Georgiadis (CERTH), C. Klanke (TUDO), F. Corominas (P&amp;G), M. Georgiadis (CERTH)</td>
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<tr>
<td>V0.2</td>
<td>14 October 2019</td>
<td>Quality control</td>
<td>C. de Prada (UVA)</td>
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<tr>
<td>V.03</td>
<td>22 October 2019</td>
<td>Further additions and improvements</td>
<td>S. Engell (TUDO) , C. Klanke (TUDO)</td>
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<tr>
<td>V1.0</td>
<td>30 October 2019</td>
<td>Finalized</td>
<td>M. Georgiadis (CERTH)</td>
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<tr>
<td>V1.0</td>
<td>31 October 2019</td>
<td>Final Approval</td>
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1 Executive summary

WP4 focuses on the development of mathematical models and solution algorithms for the optimisation of production scheduling of mixed batch and continuous industrial facilities. All model and algorithmic developments have been inspired by the P&G and FRINSA use cases. Both companies provided all the necessary data to CERTH and TUDO to investigate efficient solution approaches and perform extensive validation studies. All validation studies reveal that the optimisation-based scheduling approaches result to good quality schedules with significant benefits in terms of changeover and makespan minimisation. More specifically, several validation studies regarding the P&G use case revealed, both for the current and the agile plant layout, that the generated schedules fully satisfy the plant constraints and significant improvements can be achieved in terms of changeover minimisation. Furthermore, two representative case studies related to the FRINSA use case have been solved using realistic data, satisfying all the operational and technical constraints while resulting in significant changeover minimisation. It has been concluded that the proposed mathematical frameworks developed in Tasks 4.1 and 4.2 can be successfully applied to large-scale industrial problem instances considering both makespan and total changeover time minimisation. All results lead to near optimal scheduling solutions in reasonable computation times.

2 P&G use case

2.1 Description of P&G plant

The scheduling problem under consideration is posed by a real-life, large-scale industrial plant, of a multi-national consumer goods corporation. More specifically, a large variety of fast-moving consumer goods (FMCG) is produced on a daily basis for different purposes. The packaged products are distributed to several countries and customer centers, depending on their specific features. The production facility of a P&G plant, located in Amiens, France, constitutes the basis for the proposed modelling and optimisation scheduling frameworks. Soluble Unit Dose (SUD) pouches (also known as Pods) are produced in many different variants, for different purposes and countries. A plethora of raw materials and base liquids are transformed into intermediate products through a continuous production/formulation process. Intermediate items are packaged in several sizes and types. The high degree of diversification in the raw materials, enables the production of a huge variety of final products. The main production stages are illustrated in Figure 1.
Due to the wide range of raw materials, the different package types and sizes, the diverse kinds of labels, and other product-dependent features, a large number of changeovers take place in both stages, thus resulting in large production downtimes, higher usage of human resources and unnecessary energy consumption. Furthermore, frequent changes of raw materials, used in the formulation stage, lead to the generation and the accumulation of undesirable amounts of byproduct waste. The generated liquid waste is recycled, so that small amounts of it are reused into the next production campaigns without affecting the product’s quality (Figure 2). The limited storage capacity of liquid waste, imposes an upper bound on the total number of liquid changeovers on a daily basis. All changeovers take place simultaneously in the two stages and therefore, the most time-consuming changeover determines the total changeover time for a product sequence. Changeover times must be explicitly considered, as they constitute a key feature of the production process. The minimisation of the total changeover time is the overarching target of the plant, as it significantly improves the plant’s productivity, by decreasing the equipment idle time and the generation of byproduct liquid waste in the production stage.
The short-term scheduling horizon of interest is usually one week (or less) and both the packing and the production units operate continuously 24 hours per day. Full demand satisfaction must be achieved and strict due date constraints must be satisfied, since products have to be delivered on time to the customer’s centers. Various planned maintenance activities take place as determined by the ERP system of the plant. Once a product campaign starts, it must be carried out until completion without interruption, as the splitting of product orders is not allowed due to the underlying industrial policy. One of the main challenges faced by the planning engineers is the highly volatile demand, which makes the production environment extremely dynamic. Frequently, late-order arrivals, or sudden order cancelations, impose the need of several modifications in the initial production schedule on a daily basis. Consequently, there is a significant need for the quick generation of good quality schedules, that will assist the production engineers in their effort to develop rigorous scheduling plans under dynamic demand changes.

In general, the large number of products and the high production flexibility increase the complexity of the scheduling problem significantly. Currently, each production unit is strictly connected to only one packing line. In order to overcome the limitations of the current plant layout, the utilisation of an agile plant layout is also considered. The two stages could be decoupled by installing an intermediate buffer aiming to synchronize the different production rates of the two stages.

Production scheduling is currently performed in a semi-automatic way, as it is depicted in Figure 3. Customers’ demands are downloaded from the SAP system into the planning tool (OMP). This planning tool takes into account the demand and various technical constraints of the plant (e.g. availability of equipment, operators, raw materials, packing materials, inventory levels, etc.) and as a result, a daily feasible production plan is provided. Then, some manual checks and modifications (last minutes orders, last minute changes, etc.), are carried out by planners and the production schedule is uploaded in the system. Due to these manual operations, the high complexity and the lack of an automated iterative procedure, the optimisation of the production schedule is presently impossible.
2.2 Current plant layout

According to the current plant layout, fully flexible product allocation is allowed in the production stage and each intermediate product can be produced in any of the available production units. Since the production stage is overdesigned, the related scheduling decisions do not need to be decided in detail. On the other hand, the packing stage consists of several non-identical packing lines. Underlying production policies often assign products to selected packing units. Both stages operate in a continuous mode. As there is no intermediate storage capacity between the two stages, intermediate products are transported directly to a set of parallel packing lines. Due to the lack of intermediate storage capacity and according to other design limitations, each production unit is strictly connected to only one packing line. The packing stage is described as the most time-consuming process and constitutes the main production bottleneck of the plant. The current plant layout is depicted on Figure 4.

More than 300 different final products are scheduled weekly in the parallel packing lines. The problem under study is focused mainly on the scheduling of the packing stage, which currently constitutes the main production bottleneck. However, all necessary technical and operational constraints, related to the production stage, have to be considered to avoid the generation of infeasible schedules. In most cases, one intermediate product leads to more than one final products. The changeover times differ among the various sequences, depending on the package size, the package color, the cardboard, the label etc. All changeovers in the two stages take place in parallel and as a result, the most time-consuming changeover determines the total changeover time for a product sequence.
2.2.1 Validation studies – Current plant layout

Two precedence-based MILP mathematical models have been proposed for the scheduling problem of this large-scale continuous plants. The proposed mathematical frameworks are inspired by the scheduling optimisation problem of a P&G plant, located in Amiens, France. In particular an immediate precedence and a unit-specific general precedence MILP model for continuous processes are introduced for medium problem instances. The proposed MILP models constitute the core of two decomposition strategies which are capable to solve larger problem instances. A detailed description of the proposed mathematical frameworks has been presented in deliverable D4.3.

In order to assess the applicability of the proposed approaches, a large number of validation studies has been performed. Various schedules were generated, using historical data of the plant. The generated schedules were evaluated by the plant operators and detailed comparisons with the schedules currently implemented at the plant were made. Several problem instances were considered, including various number of final products and different product allocation policies. All the necessary data, such as product demand, due dates and processing rates were provided by P&G.

Due to the current plant operation policy and other design restrictions, each final product can be assigned to selected packing lines. As a result, two scheduling subproblems can be faced, instead of solving the initial large-scale problem. In particular, each subproblem consist of 3 parallel packing lines. The holistic MILP approach (approach A) is an efficient solution approach for medium size problems with up to 60 products and 3 packing lines. For larger problem instances, two decomposition-based solution algorithms (approach B and C) are utilized.

According to preliminary validation studies, all the operational and technical constraints are fully satisfied. Constraints related to the production stage are efficiently taken into account. A significant reduction of the total changeover time is achieved in comparison with the schedules which are currently implemented in the plant. Reductions of changeover times by up to 25% can be achieved, which translates into a 2% productivity gain.

An indicative Gannt chart, depicting the schedule of 63 final products in 3 packing lines is illustrated in Figure 5. As it is mentioned above, small or medium sized problem instances can be directly solved by the proposed immediate precedence MILP model. A higher degree of products allocation flexibility is allowed in this case. Problem instances with low products allocation flexibility have also been studied. An indicative Gannt chart is illustrated in Figure 6.
For larger problem instances, the usage of the holistic MILP approach is not efficient, as the computational cost becomes prohibitively high and as a result, not even a feasible solution can be generated in reasonable computational times. Hence, the utilisation of decomposition strategies is necessary. With these, nearly optimal solutions are provided in acceptable computational times. An indicative Gantt chart depicting the schedule of 130 final products in 3 packing lines is illustrated in Figure 7.
Besides the full satisfaction of the operational constraints, the efficient integration of the planned maintenance activities into the generated schedules is of great importance for the plant. Each maintenance or cleaning process is represented by a “dummy product order” which are inserted into the production schedule by fixing their allocation and their completion variables. An indicative Gantt chart is presented in Figure 8, depicting the efficient integration of the maintenance operation into the final schedule.

According to the underlying inventory constraints of the plant, some products have to be produced, during a strictly defined time window. These production campaigns cannot start before a lower time limit, but also without exceeding their related due dates. An indicative Gantt chart, is presented in Figure 9, depicting a problem instance, in which production orders which have to be produced within a specific time slot are included.

The last production campaigns produced before the time horizon of interest are also considered into the final solutions, by taking into account the related changeover times. In particular, “dummy production orders”, with zero production time, and the same features as the last production campaigns of the previous schedule, constitute the first production orders of each packing line. Hence, possible time-consuming changeovers that are related to the first product of the sequence of each packing line are avoided if possible.
In the course of this study it was revealed that it is often necessary that the generated schedules can easily be modified by the plant operators, to account for unexpected events, such as new order arrivals or order cancellations. Therefore, the industrial requirements impose an upper bound on the total computational time. A time limitation has been set for the solver and all solution times are less than 20 CPU minutes which is fully acceptable for the plant operators. All models were implemented
in GAMS (General Algebraic Modeling System), and solved utilizing the IBM ILOG CPLEX 12.0 solver on an 3.60 GHz Intel Core i7 7700 processor and 16 GB RAM.

In order to further evaluate the proposed mathematical frameworks, an efficient tool chain has been developed, in collaboration with the plant engineers, to facilitate data exchange through a direct communication of GAMS and the ERP systems of the plant. P&G has validated the proposed MILP-based optimisation approach using real production data from the P&G plant. To make this possible, a new piece of software had to be developed in order to gather all the necessary data. This software has been developed internally in P&G using the VB.net platform. A detailed representation of the software is illustrated in Figure 10. This tool gathers all important data from different internal systems (SAP, formulation database, production historian database, production machine-events database). A Microsoft Excel file which includes customers demand, products special features, due dates, and other essential information is generated. This tool then launches GAMS automatically with the script containing the MILP-based framework. Once the optimized schedules are generated, they are exported to an output Excel file. The visualisation via interactive Gantt charts provides the decision makers with flexibility and allows them to make the necessary adjustments prior to the final application of the proposed schedules.

![Figure 10: Setup for short term validation of the models developed by CERTH](image)

As a future work item and medium-term goal, P&G will integrate the aforementioned optimisation tool in the plant IT infrastructure so that on-line validations can be performed, once the daily production plan is available. The overarching target is to generate optimized productions sequences that can be sent to production in such a timeframe (on-line) that they can be used to plan the daily production, as a demonstration of the solution within the CoPro project.
2.2.2 Concluding remarks

The proposed approaches can provide very important support to the decision makers in order to cope with challenging scheduling problems that are typically met in industrial facilities. According to the validation studies, the proposed MILP-based mathematical frameworks can efficiently generate solutions which satisfy all the necessary constraints. According to the industrial limitations, good quality solutions are provided within acceptable computational times. The usage of the proposed mathematical approaches can lead to significant productivity gains and changeover reduction. The impact of scheduling optimisation on the overall performance of an industrial facility was evaluated and clear evidence for the need of using optimisation-based techniques for challenging scheduling problems has been provided. The accuracy of the data is vital for the solution quality, hence the direct connection of the scheduling methods with the EPR system via integrated tools is critical.

2.3 Agile plant layout

A limitation of the current layout is the necessity to synchronize the production rates of the two stages within a line. Since the processing rate of the packing lines lies are, depending on the product, larger or smaller than the processing rate of the formulation lines, the bottleneck of the process could be either in the formulation or the packing stage. The packing lines can only process certain products while all units of the formulation stage are identical, i.e. each unit in the formulation stage can process every product. Changeovers occur in both stages of the process depending on the composition of the current and the subsequent product. In order to reduce the total changeover time and to utilize the higher processing rates in each stage, the two stages could be decoupled, as shown in Figure 11. In this layout, the products can be transferred from any formulation line to any packing line. The use of an intermediate buffer provides the necessary flexibility to enable desynchronisation by storing intermediate products.

![Figure 11: Plant overview - Agile layout](image)

2.3.1 Proposed solution approach

A discrete-time MILP model augmented with a precedence-based MILP presorting model was proposed. The discrete time MILP model solves the timing and allocation problem in the agile layout. At the same time, it tracks the level of each product family, i.e. the distinct types of pouches that are produced in the formulation lines at every discrete time point.

As the discrete-time model does not provide explicit sequencing information for every production line, the changeover times cannot be optimized directly. An option to explicitly represent the changeovers is to extend the model by precedence variables. However, this requires many new
inequality constraints and therefore increases the model size considerably. This is undesirable with respect to the computation time and memory constraints.

Consequently, in addition to the discrete-time model an immediate precedence-based has been developed. By using the latter, the allocation and sequencing decisions of certain packing lines are fixed prior to the solution of the discrete-time model. The precedence-based model has a drastically reduced size compared to the discrete-time model, and therefore longer prediction horizons are possible.

In order to maintain enough degrees of freedom in the discrete-time model, e.g. to still be able to satisfy the buffer mass balance and capacity constraint, the precedence-based model is only applied to a subset of packing lines and the formulation stage is not considered at all. The buffer mass balance is neglected because the discrete-time model takes care of it in the second step.

As the planning time horizon usually is 3 days of non-stop production, the problem instances become large, e.g. weekend schedules with around ninety products are generated. Due to the high number of decision variables resulting from the high temporal resolution in the discrete-time model, a tailored decomposition strategy is applied. The decomposition approach is based on splitting the original set of orders into smaller subsets which are then scheduled iteratively. The set of products that are scheduled by the discrete-time model are taken from the sequences proposed by the precedence-based model to reduce the changeover times in each iteration. A heuristic chooses the subset of products scheduled by the discrete-time model in each iteration. Finally, in each iteration, the timing and allocation of the previously scheduled products are fixed, resulting in computationally tractable subproblems.

The feasibility of the sequences that are determined by the precedence-based presorting will be guaranteed by the discrete-time model by taking appropriate timing decisions.

One important technical constraint is the satisfaction of product-specific deadlines. For the order decomposition a list of orders is created prior to the optimisation. For a subset of products from this list the precedence-based presorting is conducted. The order heuristic picks products from the initial list and the sequences presorting provides the set of orders that are scheduled by the discrete-time model in each iteration. The heuristic preferably picks products with the nearest deadlines. If there are multiple products with the same deadline, the product with the lowest flexibility is taken. This procedure guarantees that products with early deadlines are scheduled first and deadline constraints can be met.

Not all products can be packed on all packing lines and each product can be scheduled on at most two different lines. In the discrete-time model these eligibility constraints of the packing lines are considered by simple product-specific logic constraints.

To obtain an equal load on all packing lines it is beneficial to pick a set of orders in each iteration which can be scheduled on as many different lines as possible. However, products with a low flexibility are scheduled first in order to avoid that the lines which can handle these products are filled with products that can also be produced on others.

2.3.2 Validation studies – Agile plant layout

The testing and validation studies focused on the utilisation of the intermediate buffer and the reduction of changeover and idle times. Furthermore, it was checked if all technical constraints were
satisfied by the generated schedules. As the plant in Amiens is producing continuously, it cannot be assumed that the buffer is empty when a new schedule is executed. Thus, different initialisation strategies have been proposed and tested, as well as different initial buffer levels.

Figure 12 shows a schedule generated by the solution approach introduced in subsection 2.3.1. The first six lines “Line1L” to “Line6L” represent the formulation lines. The second six lines “Line1P” to “Line6P” represent the packing lines. The numbers above the bars indicate the product family produced. The bars in the formulation lines are coloured identically, as they do not represent different final products as it is the case in the packing lines. Black bars between the product bars indicate changeover times, while dotted lines indicate idle times. The vertical bold dashed grey line represents a deadline. In this case the first product on each packing line which must be produced before March 16 at 8 AM. The deadlines are easily satisfied. All other products must be produced prior to March 18. As the deadlines originate from the current layout which exhibits an overall smaller throughput, demand satisfaction is easy to reach with the flexible layout.

Load balancing is successful on the formulation lines and within, but not between, the packing lines “Line1P” to “Line3P” and “Line4P” to “Line6P” respectively. The reason for this is that the packaging of a specific product can either be done on the first or the last three packing lines, but never on two different lines from these two distinct sets of packing lines.

To assess the benefits of the flexibilized layout in comparison to the coupled layout, the true schedule for 2019-03-15 was computed. It is displayed in Figure 13. Similar to Figure 8 six production lines are displayed. What can immediately be seen is that the true schedule takes almost a day longer to finish production in “Line4” to “Line6”, while in “Line1” to “Line3” it takes up to 12 hours longer. Overall the flexibilized layout provides significant benefits in throughput over the decoupled layout. In Table 1 the makespan and completion times of the two different layouts are compared for the 2019-03-15 schedule with and without precedence-based presorting for the flexible layout.

Two reasons for the huge benefits exist. First of all, the current production rates of the individual packing lines are different and on average significantly smaller than those which have been provided by P&G to compute the schedules for the flexible layout. With minor changes to the processing equipment, the increased processing rates will be realised in the plant in the near future. Secondly, the stage desynchronisation takes the desired effect and neither formulation stage lines nor packing stage lines need to decelerate production due to the other stage. Changeover times are difficult to compare, because the largest changeover over all product properties determines the overall changeover time from one product to the next. As the set of properties in the flexible layout is
divided into formulation properties and packing properties and in both stages the sequences are different, no concise comparison is possible.

![Figure 13: True production schedule from 2019-03-15 with six products scheduled per iteration, deadline constraints and 50% of maximum initial buffer level and with precedence-based presorting.](image)

In principle only the discrete-time model is necessary to provide feasible schedules. Yet when the precedence-based presorting is additionally employed, the changeover and idle times are improved to a great extent. Table 1 shows that the precedence-based presorting helps to improve all schedule quality criteria at decreased computational time. The reduction in computational time results from the decision variables which are fixed by the precedence-based presorting and the decrease in idle time. When idle times are introduced, the solution time typically grows significantly. For this calculation, the precedence-based model scheduled up to twelve products per iteration in the packing lines, while the discrete-time model schedules six products per iteration. The high relative decrease in idle time can be attributed to the overall small total idle time present in both schedules.

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As the level limitation of the buffer couples the formulation lines and the packing lines tightly, the buffer level can lead to idle times in the formulation lines as well as in the packing lines. This depends on the specific case considered, the assumed initial buffer level and the decomposition parameters. Since the average processing rate in the formulation stage is usually higher than in the packing lines, the mass in the buffer tends to increase continuously. With non-stop production of formulation lines and packing lines, the buffer will be filled to its capacity limit at some point in time. This then leads to idle times in the formulation lines until the packing lines drained the buffer sufficiently. Still there are many products in the packing lines, especially when the casing is a so called “B tub”, which exhibit a high processing rate compared to the formulation lines. In this case the packing lines might have to wait until enough pouches are produced and idle times are also inevitable.

The latter effect, namely idle times in the packing lines, can be seen in Figure 14. A schedule for a planning horizon of five days, containing 163 products from 2019-04-05 is depicted.
Only in the packing lines idle times can be observed. An example of inevitable idle times can be seen by looking at “Line2L” and “Line5P”. The product packed from product family 38 needs to wait until the pouches are produced in the formulation line. As the formulation lines are tightly packed the production of the pouches for product family 38 cannot be scheduled earlier. Also, as the buffer has been initialized not containing any pouches, no spare pouches could be utilized to start packing earlier. All other idle times in this schedule are the result of the faster processing rate of the “B tub”-products compared to the formulation lines.

Figure 14: Five days optimized production schedule from 2019-04-05 with six products scheduled per iteration, deadline constraints and zero initial buffer and without precedence-based presorting.
The opposite effect of idle times being introduced in the formulation lines by a buffer operated at its upper bound can be observed in Figure 15. Here a weekend schedule from 2019-03-22 is displayed with 94 products and an initial buffer level of 90% of the maximum value. The maximum buffer level is assumed such that the buffer can hold up to eight hours of non-stop pouch production in the six formulation lines. In this case almost no idle times except for in the beginning in “Line6P” can be seen.

In Figure 16 the corresponding buffer level evolution with a “uniform” initialisation approach, meaning the initial buffer level of each product family is chosen to be equal, can be seen. The dark blue line at the top of Figure 16 marks the maximum buffer level. The black line indicates the total buffer level, while the coloured lines are the buffer levels of the individual product families. What can immediately be seen is that no product family buffer level drops below zero and the total buffer level stays within its bound.

During two time periods the buffer level is very close to its maximum value. If these time periods are compared to their counterparts in Figure 15, it can be seen that idle times in the formulation lines are introduced whenever the buffer level is close to the maximum value. As indicated before this due to the processing rates of the formulation lines being on average larger than those of the packing lines.

Another initialisation approach that was tested is the “weighted” initialisation. Herein the share of a product family in the initial buffer level is determined from the number of times it is used within the whole planning horizon. With the given distribution of the production demands, this initialisation approach has been extended to exclude rarely used product families. The less often a product family
is used in the packing stage the smaller is the benefit of keeping such pouches in the buffer from the previous production days. Rarely used product families in the buffer result in an unnecessary decrease of the buffer capacity.

Figure 17 and Figure 18 show the same case study from 2019-03-22 as Figure 15 and Figure 16. All settings are identical except for the initialisation approach. Only product families with more than 5 different products in the packing stage are initially stored in the buffer, filling the buffer up to 90% of its capacity. This criterion only applies to three product families. All other product families are not available in the buffer initially.

This “weighted” initialisation approach has the disadvantage that if product families are scheduled primarily to the end of the schedule the initial product family buffer value decreases the buffer capacity until the pouches are finally used. This problem applies to the two product families represented by the red and the blue curve. For those the utilisation in the beginning is small and both product families reduce the buffer capacity in the beginning. Yet, for the product family represented by the yellow curve, a quick utilisation takes place.

As it is unknown how the actual buffer levels at the end of a working week will be, different buffer initialisation scenarios were tested. When comparing the results obtained using both initialisation approaches, as displayed in Table 2, no initialisation approach seems to exhibit clear benefits over the other. The total idle time, makespan and completion time of the uniform initialization approach are smaller, but the changeover time increased.

![Figure 17: Production schedule from 2019-03-22 with six products scheduled per iteration, deadline constraints, an initial buffer level of 90% of the maximum level and without precedence-based presorting. The buffer was initialized with the initialisation approach “weighted”.

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**D4.5 REPORT ON THE RESULTS OF THE TESTING AND VALIDATION STUDIES**
Figure 18: Buffer level plot from 2019-03-22 with six products scheduled per iteration, deadline constraints, an initial buffer level of 90% of the maximum level and without precedence-based presorting. The buffer was initialized with the initialization approach “weighted”.

Table 2: Results for the optimized schedules from 2019-03-22 with two different initialization strategies.

<table>
<thead>
<tr>
<th>Initialization strategy</th>
<th>Makespan [min]</th>
<th>Completion time 2nd stage [min]</th>
<th>Changeover total [min]</th>
<th>Idle time total [min]</th>
<th>Computation time [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>weighted</td>
<td>3444</td>
<td>16002</td>
<td>3708</td>
<td>966</td>
<td>1254</td>
</tr>
<tr>
<td>uniform</td>
<td>3366</td>
<td>15840</td>
<td>3852</td>
<td>672</td>
<td>1580</td>
</tr>
</tbody>
</table>

### 2.3.3 Concluding remarks

The proposed solution model satisfies all technical constraints of the P&G case with increased flexibility. The main challenge is to coordinate the different subproblems that are solved during the iterations. This challenge was tackled by applying a combination of a discrete-time model and an immediate precedence-based presorting model using an appropriate decomposition heuristic.

The operational mode of the intermediate buffer needs to be agreed upon, for example with respect to the products that are produced mid-week. As the initialization strategies presented here were not yet tested with different parameters and for all historical datasets available, further light will be shed on this issue in the future.

The derived schedules yield high improvements over the schedules provided by P&G for the current production setup. Schedules for one weekend of production can be computed within a reasonable amount of time.

### 3 Frinsa use case

#### 3.1 Frinsa plant layout

In this work, the canned fish production in a real-life industrial facility is considered. Specifically, the production scheduling problem of Frinsa del Noroeste S.A., located in Ribeira, Spain, is investigated using real process data. The plant under study is capable of producing more than 400 product codes,
a number that is constantly increasing, in order to satisfy the market needs, while more than 100 product orders are fulfilled on a weekly basis, making it one of the largest canned fish producers in Europe. The production process is characterized by extreme complexity, as it comprises of several batch and continuous processes. Therefore, the efficient modelling of the underlying problem requires a simplification of the process. In order to simplify the description of the production process, we identified four major processing stages, in particular, thawing, filling and sealing, sterilizing and packaging, each consisting of multiple parallel units (Figure 19). Initially, the raw materials (fish) arrive in tracks in the form of frozen fish blocks, and they need to be defrosted in the thawing chambers. Then, the blocks are chopped into the appropriate size and filled in the cans alongside with all other ingredients (tomato sauce, brine, olive oil etc.) as required by the recipe. In the same processing stage, the cans are sealed and transferred into carts. Due to health regulations, the filling and sealing lines must be cleaned after at most 30 hours of operation. In the next stage, the carts are manually transferred to the sterilizers in order to ensure the microbiological quality of the final products. After the completion of the sterilisation process, carts are manually extracted from the retorts and are transferred to the packaging stage, where the cans are packaged in their final form (6-pack, 12-pack, boxes etc.) and are stored in the warehouse to be later distributed to the market. An important operation of this stage is labeling. However, not all packaging lines have an individual labeler. In particular, lines 1-2 and 5-6, share the same labeling machine, therefore they cannot operate simultaneously. Finally, after the completion of the packaging stage, the end products are stored in the warehouse.

The plant under consideration can be identified as a multiproduct, multistage facility with both batch (thawing, sterilizing) and continuous (sealing and filling, packaging) processes, each utilizing multiple
parallel units. Additionally, the large production demand and high production flexibility increases significantly the complexity of the plant. The thawing stage is overdesigned compared to the processing capacity of all other stages, therefore it is a valid assumption to omit it from this study. Unfortunately, otherwise no clear bottlenecks exist, and as such all other processing stages need to be modelled. The plant operates from Monday to Friday, however in cases of large weekly demands overtime operation during the weekend takes place. Therefore, the short-term scheduling horizon varies from 5 to 7 days depending on the case study, where all processing units are available 24 hours each day. Most orders have a single due date at the end of the scheduling horizon of interest; however, exceptions may occur. A make-to-order policy is followed and tardiness is not allowed, therefore all orders must be completed prior to their due date. Moreover, a single campaign policy is imposed by the industry, thus order splitting is not allowed. Finally, it must be emphasized that a non-preemptive operation is necessitated due to product quality considerations and space-related limitations.

3.2 Validation studies

An MILP-based solution strategy has been proposed to address the scheduling problem of the Frinsa plant, described in the previous section. More specifically, the suggested mathematical framework comprises three main pillars, i) a batching algorithm that translates the products orders into batches that are to be processed, ii) an MILP model responsible for the extraction of optimal scheduling decisions and iii) an order-based decomposition strategy that leads to the generation of near optimal schedules in CPU times acceptable by the industry. Two novel MILP models are developed using an aggregated approach to reduce the size of the model. In particular a general-precedence-based (M1) and a unit-specific-general-precedence-based model(M2) have been developed. The models can be used interchangeably with the suggested solution strategies, depending on the overarching goal. In particular, model M1 is used when the minimisation of the makespan is considered while M2 is used to address scheduling problems whose main goal is the minimisation of the total changeover time. A detailed description of the proposed mathematical frameworks has been presented in section 3 of deliverable D4.2.

The multiproduct, multistage, semi-continuous plant under consideration consists of four processing stages, i.e. thawing, filling and sealing, sterilisation and packaging. However, the utilisation of the proposed aggregated approach reduces the optimisation problem into two continuous processes (filling and sealing, and packaging). Exact schedules are generated only for these stages. However, due to the assumptions and the imposed feasibility constraints of the aggregated approach, the proposed schedules can be realized by all stages, without violating any capacity or other limitations. The total number of available sterilizers in the plant is 16 and they are modelled as a common renewable resource. Relevant labeler constraints are also introduced in the packing stage. In particular, the pairs of packaging lines \{P_1; P_2\} and \{P_5; P_6\} share the same labeling machine, therefore it is forbidden to operate simultaneously. The plant is operating from Monday to Friday, however in periods of high product demands, overtime production during the weekends may occur. Therefore, a 120- or 148-hour horizon is considered depending on the problem instance. The implementation of a discrete-time grid requires the discretisation of the relevant scheduling horizon into periods of equal length. A duration of one hour is chosen for each time period, since the longest sterilisation process lasts 82 minutes. Employing a finer discretisation may provide more exact solutions but the computational cost is prohibitive for the solution of the problem in reasonable CPU
times. A challenging prerequisite set by the production engineers is that the total computational time required for the generation of near optimal schedules has to be less than 15 minutes. This is a relatively small CPU time for weekly scheduling, however, such a low solution generation time will allow production engineers to run multiple what-if analyses and re-run the model whenever new information arrives in the plant. Meeting this constraint thus makes the computer-aided scheduling tool much more appealing to the production engineers and plant managers.

All models and solution strategies have been developed using the GAMS 25.1 interface and all instances were solved in an Intel Core i7 @3.4Gz with 16GB RAM using CPLEX 12.0. An optimality gap of 3% was used in each iteration of the solution strategy to ensure the generation of optimal schedules for every MILP sub-problem of the decomposition algorithm.

### 3.2.1 Real Case I.

In this case, the scheduling problem of Frinsa del Noroeste is studied for a time horizon of 5 days. The orders for 100 products were directly provided by the ERP system and correspond to the real demand profile scheduled by the production engineers in the plant. All demand-related data are deterministic, and the use of OEE rates increases the robustness of the proposed schedules to breakdowns. The problem was solved twice, once having as the objective the minimisation of the makespan and once the minimisation of the changeovers.

Firstly, we used the suggested method with model M1 to examine the minimisation of production makespan. Various insertion policies for the decomposition strategy were tested, as shown in Table 3. As expected, a finer decomposition of the initial scheduling problem leads to lower CPU times, but also to worse objective values. Given the computational time limitations, the best policy for this problem is to insert the product orders 20-by-20 in the optimisation model. The less decomposed problem using a 40-by-40 order decomposition does not provide better solutions, since the time limit is reached, and a worse integrality gap results. A monolithic approach cannot provide any integer solution within the allowed CPU time. The production schedule suggested and realized by the schedulers required a single 8-hour shift on Friday \( C_{max} \approx 104 \), which is far worse than the generated schedule by the proposed solution strategy. Even when we apply a simple 1-by-1 insertion policy, we get results comparable to the solution proposed by the schedulers. This is achieved in an automated manner and in less than 2 minutes.

<table>
<thead>
<tr>
<th>Insertion policy</th>
<th>Objective (h)</th>
<th>CPU time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-1</td>
<td>104.6</td>
<td>94</td>
</tr>
<tr>
<td>2-2</td>
<td>97.6</td>
<td>120</td>
</tr>
<tr>
<td>5-5</td>
<td>96.0</td>
<td>159</td>
</tr>
<tr>
<td>10-10</td>
<td>95.3</td>
<td>221</td>
</tr>
<tr>
<td>20-20</td>
<td>94.4</td>
<td>356</td>
</tr>
<tr>
<td>40-40</td>
<td>94.6</td>
<td>900</td>
</tr>
</tbody>
</table>

*Table 3. Comparison of insertion policies (makespan minimisation)*
Next, we tested the efficiency of model M2 in combination with the suggested solution strategy to address the changeover minimisation objective. Again, we investigated various insertion policies, in order to decide on the most appropriate one, according to the imposed solution time limitations. In contrast, to the makespan minimisation, the products are now scheduled in order to minimize the total changeovers. Thus, no consideration of processing the orders as soon as possible exist. As a result, the fixed decisions on unit allocation and general precedence on products scheduled on previous iterations may lead to infeasible situations for the products yet to be scheduled. This occurs in the 1-by-1 insertion policy as shown in Table 4. In order to avoid this situation, the problem must be decomposed to a lesser degree. The best results are generated when a 5-by-5 insertion is employed, in which a total changeover time of 42.7 hours is achieved, a solution that represents a 10-15% improvement compared to the one proposed by the schedulers. Inserting more products in each iteration could not further improve the objective, since no integer solution is found within the allowed CPU time. In general, changeover minimisation is a more difficult objective due to the utilisation of the unit-specific general precedence model M2, which necessitates the further incorporation of immediate precedence variables and more sequencing constraints compared to model M1, thus leading to larger and more difficult problems to be solved.

<table>
<thead>
<tr>
<th>Insertion policy</th>
<th>Objective (h)</th>
<th>CPU time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-1</td>
<td>Infeasible</td>
<td>-</td>
</tr>
<tr>
<td>2-2</td>
<td>43.5</td>
<td>89</td>
</tr>
<tr>
<td>5-5</td>
<td>42.7</td>
<td>850</td>
</tr>
<tr>
<td>10-10</td>
<td>-</td>
<td>900</td>
</tr>
</tbody>
</table>

An inevitable characteristic of the applied decomposition algorithm is that the size of the model continuously increases with each iteration. Let us consider the 20-by-20 policy for the makespan minimisation problem, where a total 5 iterations of model M1 are solved. The number of binaries in the 5 MILP models generated are 9319, 18604, 29150, 43684 and 48144. Consequently, the problems are getting harder and take more time to be solved. The main reason for this increment is the increase of the number of pairs of sequencing decisions that are not fixed, alongside with the variables that are used for the feasibility constraints, which employ the discrete time-grid. In order to reduce the model size, we could fix all timing decisions (starting and completion times) after each iteration in the decomposition algorithm. However, this approach is less flexible and results in much worse scheduling decisions.

3.2.2 Real Case II.

In this case, we examine another problem instance of the same facility, however, this one represents a week during the most demanding production period of the year. A total of 123 products must be scheduled, a number that is significantly larger than the one examined in case I., which results in a
scheduling problem of extremely high combinatorial complexity. The total demand is such that an overtime production is unavoidable; therefore, a scheduling horizon of 7 days is chosen.

Model M1 is employed with a 20-by-20 insertion policy to propose a minimum makespan production schedule. The proposed solution strategy generates a near optimal schedule in less than 10 minutes. A makespan of 133.1 hours is achieved, which compares favorably with the solution proposed by the schedulers. The executed weekly schedule demanded the uninterrupted operation of the plant throughout the weekend ($C_{\text{max}} \approx 148\text{h}$), thus the proposed solution significantly reduces the overtime production. In Figure 20 the Gantt chart of the proposed schedule is illustrated for both the filling and sealing and packing stage. Each colored block indicates the production of a single product. Notice that the labeler constraints are respected and at no point a simultaneous operation of pairs of packing lines 1 – 2 and 5 - 6 occurs. Moreover, the number of utilized sterilizers never exceeds the total available resource installed in the plant (16 sterilizers) as depicted in Figure 21.

Figure 20: Gantt chart (makespan minimisation).
Changeover minimisation was considered using model M2 and a decomposition algorithm, in which products are inserted in a 5-by-5 fashion. The proposed schedule was generated in just under 15 minutes and the total changeovers required were reduced to 62.6 hours. Compared to the executed schedules an improvement of around 15% is accomplished, while the generated schedule has been fully validated by the production engineers of the plant. Figure 22 depicts the Gantt charts for both continuous stages. It is shown that choosing the minimal changeovers for each stage has a negative feedback on the total production time, since a worse synchronisation between processes is achieved.
4 Concluding remarks

This deliverable describes representative validation studies of models, solution algorithms and methodologies developed in Tasks 4.1 to 4.3. More specifically, the optimal production scheduling of large-scale, real-life industrial facilities is considered. The overall scheduling problems are characterized by a very large combinatorial complexity. The industrial facilities under consideration are described by multiple production stages, each consisting of multiple parallel units, and both continuous and batch processes exist. A large number of products must be processed within a scheduling horizon under tight operating and design constraints, thus resulting to a very large number of decisions to be made. The suggested solution strategies are successfully applied to several real-life industrial problem instances considering both makespan and total changeover minimisation.
Optimal weekly schedules are generated in low computational times. All schedules have been fully validated by the industrial partners and compare favorably to the schedules developed by the decision makers. The proposed optimisation frameworks can be easily extended to address similar large-scale scheduling problems of continuous or semi-continuous processes, which are very common in food and packaged goods industries. Moreover, they can be the core of a computer-aided tool that will assist decision-makers to generate fast and near-optimal schedules.