Routing flexibility is a key process feature in supply chains characterised by complex hierarchy at different manufacturing levels. When routing alternatives exist, controlling the supply chain to ensure uniformity and quality of the production outcome becomes a significant challenge, also from a demand planning perspective. In this paper, the demand planning problem at a supply chain operating in the semiconductor industry is investigated. Special attention is paid to mid-term demand planning when production orders are not yet finalised and aggregated demand forecast is considered. Within this planning frame, the demand planners face the difficult task of disaggregating aggregated demand into finer granularity products in order to generate provisional production plans that will be used to foresee potential capacity adjustment requirements.

The demand disaggregation process entails routing decisions that also incorporate restrictions occasionally imparted by final customers on eligible routes for a specific product type. Historical demand patterns and routing constraints currently constitute the main decision drivers in the demand disaggregation process; likewise, the only objective accounted for is the timely satisfaction of customers’ orders. However, disregarding capacity constraints and ignoring incoming future demand characterised by more stringent routing requirements leads to uncapacitated production plans which might cause significant lateness in the orders’ production. In this study, simulation-based solution approaches able to facilitate the demand planners in the complex task of disaggregating demand forecast are developed. It is shown how either analytical simulation algorithms or discrete event simulation can be used to quantify the lateness deriving from the allocation of different demand profiles and predict the impact of future demand on the optimal disaggregation logic. For analysis purposes, the supply chain will be modelled as a serial-parallel multistage manufacturing system for which the facilities operating in parallel at each stage are similar from a process viewpoint but present different capacity.

1. Introduction

Flexibility provides a strategic capability for supply chains that want to sustain an advantage in highly competitive manufacturing markets [1]. In order to generate real value proposition in the supply chain, single facility flexibility is not sufficient and an external organisation integrated perspective for flexibility issues should be adopted [2,3]. Routing flexibility has been identified as one of the most relevant aspect of process flexibility in a supply chain [4]. Routing flexibility refers to the possibility to redirect the production flow to alternative production routes in order to deal with uncertainties, such as breakdowns or overloading of machines/plants [4]. Despite the advantages of routing flexibility in terms of productivity, there are also drawbacks. Indeed, the presence of routing alternatives makes the entire system complex to manage as the uniformity and quality of the production outcome can be compromised. In this study, routing flexibility is considered in the demand planning problem of a highly flexible and vertically integrated supply chain in the semiconductor industry. In medium-term planning, demand forecast is expressed at an aggregated level and the demand planners face the complex task of disaggregating it into finer granularity at product level. As
production routes are associated with finer granularity product levels, the disaggregation decision also involves the choice of the best option among alternative routes available for a certain product order. The production route identifies the facilities visited by a product order through the various levels of the supply chain. In the supply chain analysed, the production flow is serial through the consecutive levels and one facility per manufacturing level is visited. In this study, capacity allocation strategies are developed so that the routing choice is optimised and the global production lateness is minimised. The generation of optimal disaggregation plans for specific aggregated demand forecasted at a certain week is based on an algorithmic procedure that enhances the logic currently adopted in the planning system as considerations on capacity available and future demand scenario are incorporated. Variants of the basic allocation logic have been developed to accommodate different allocation priority preferences.

The allocation of production orders to specific production routes presents conceptual similarities with the hybrid or parallel flowshop scheduling problem. This problem focuses on scheduling a certain number of jobs in a flowshop characterised by machines operating in parallel at each production stage [5]. Order sequencing optimisation is generally performed to minimise the makespan. Extensive literature is available on this problem and a comprehensive review of the solutions developed can be found in [6,7]. The main differences between the hybrid flowshop scheduling problem and the disaggregation problem investigated in this study is that more flexibility is allowed for the latter in terms of order quantity and type; indeed, the aggregated demand can be disaggregated into several product types and the number of units allocated to each product type is subjected to some flexibility. On the contrary, less flexibility is applicable to routing as the choice of facilities at different manufacturing levels is not independent.

Another novel element with respect to the classical implementation of the hybrid flowshop scheduling problem consists of the time concept adopted for the planning logic. The production capacity allocation to a specific order does not follow a time scale as the capacity available at the different manufacturing levels is referred to the production out date. Hence, the progression of an order through the supply chain does not correspond with a progression in time. This peculiar planning logic is sensible as the flow through the supply chain can be considered synchronous at mid-term planning level. The disaggregation problem has been initially modelled using an algorithmic procedure. However, due to the increasing relevance of discrete event simulation (DES)-based decision support tools as a means to facilitate supply chain management decisions [8], a process-oriented DES model of the supply chain has also been developed. In this model, events as opposed to time trigger the realisation of capacity allocation steps. A similar DES approach has been used in [9] where mathematical models developed for hybrid production control strategies are translated into DES models and solved considering time as an entity attribute rather than the triggering element of the generator processes. The models developed here and the industrial case presented will support the expansion of the simulation engine of the DREAM ("simulation based application Decision support in Real-time for Efficient Agile Manufacturing", http://dream-simulation.eu/) platform. DREAM is a research project whose ultimate objective is to provide industrial practitioners with easy-to-use, reconfigurable and efficient simulation based decision support tools for cross-functional decision processes at multiple hierarchical levels.

The study presented in this paper is a work-in-progress study and simulation results are not yet available; however, the solution variants proposed are compared on a theoretical basis and some insights into the solutions’ efficiency are provided.

The remainder of the paper is organised as follows. Section 2 describes in detail the problem investigated; the planning algorithm implemented to generated disaggregation solutions is elaborated in Section 3. Variants to the original solution are illustrated in Section 4. Section 5 provides insights into the development of the DES model; conclusions are drawn in Section 6.

2. Problem Description

A schematic representation of the supply chain investigated in this study is given in Figure 1. Manufacturing levels 1 to 3 constitute the front-end fabrication process whereas the back-end of the supply chain includes manufacturing levels 4 and 5. There are also three distribution centres where the final products are shipped before they can reach the customers. The analysis presented here focus on the back-end process, hence the back-end facilities have been highlighted with a continuous line in Figure 1. Each manufacturing level is characterised by multiple facilities that operate in parallel. The facilities at a given manufacturing level are similar from a process viewpoint but differ in terms of production capacity. Utilisation constraints generally apply to all facilities due to production quality reasons. Outsourcing is allowed and some of the facilities represented in Figure 1.

![Fig. 1. Supply chain configuration.](image)

Various product types are produced in the supply chain. Independent of the specific product, the production flow through the supply chain is serial; all the items produced visit one facility per manufacturing level following a serial order. For each product type alternative production routes are available. The product hierarchy explored during the demand planning process identifies the production routes available for
a certain product. Four hierarchical product levels are considered in the demand planning process:

1. Product family (or Plan Position, PPOS) aggregates products characterised by similar functionalities;
2. Sales Product (SP) is a product with given specifications; it corresponds with a customer ordering code;
3. Finished Product (MA) adds a specific production route to a SP;
4. Stock Keeping Unit (SKU) incorporates information on the distribution centre to which the MA will be shipped.

Table 1 reports an example of product hierarchy and alternative routes available for a specific PPOS (e.g. PPOS1). Four different SP’s are associated with PPOS1; each SP presents three alternative production routes. At a planning level, a production route is expressed in terms of the bottlenecks that an MA is required to visit; only manufacturing level 4 and manufacturing level 5 bottlenecks are considered here. For each MA, a loading factor for each bottleneck is reported (Table 1); the loading factor expresses the number of time units required at that bottleneck for each MA unit to be produced. As an example, in order to produce one MA3 unit, 1 time unit is required at bottleneck 2 (manufacturing level 4), 2.52 time units are required at bottleneck 5 (manufacturing level 5), etc… A loading factor equal to 0 suggests that the MA does not visit the corresponding bottleneck (e.g. MA3 visits only bottlenecks 2, 6, 7 and 9). It is worth noting that the difference between the routes associated to a SP can also be limited to different loading factors for the same bottlenecks so that the physical route is the same but the amount of time/capacity required at the bottlenecks varies.

The demand planning problem investigated in this study consists of generating preliminary production plans in the mid-term planning horizon. In this planning horizon, which ranges from 5 to 26 weeks, there is a certain level of flexibility in disaggregating demand; demand forecast is generally used and progressively substituted with actual customer orders as the short term planning period approaches. The short-term planning period generally consists of four weeks. Detailed production data are used for the definition of the short-term plan; variations to the short-term production plan are rarely allowed as this would cause significant production delays being the plan already converted into actual production. In mid-term planning, demand forecast is used at an aggregated level; PPOS demand is disaggregated into finer granularity products using information on historical demand patterns. Disaggregation rules, which might be adjusted according to the specific order scenario, are used to assist the demand planners in the disaggregation process. The disaggregation decisions involve the distribution of PPOS quantities across the associated SP’s, the choice of production routes for each SP and the final assignment to distribution centres. Exclusion constraints might also apply; these reduce the number of routing options available at SP level; exclusion lists are associated with specific customers’ requirements and state which facilities should be avoided for the production of certain orders. The logic behind the disaggregation rules is proprietary to the company that owns the supply chain and has not been disclosed; however, it is known that the rules apply patterns from past order history to the disaggregation of specific PPOS’s. No information on the supply chain current capacity is used when a PPOS is disaggregated or when production routes are chosen for the various SP’s. Hence, uncapacitated production plans are generated and lateness in satisfying customers’ orders is likely to be experienced. In order to avoid this, preliminary production plans should be derived from both the analysis of historical data and considerations on the capacity available.

3. Planning Algorithm

In the solution elaborated in this study, historical order patterns will be used to disaggregate PPOS into SP’s. This is based on the consideration that SP’s variations would mean variations of the ability to fulfil customers’ orders; customer orders can be forecasted with a sufficient level of accuracy; hence, the disaggregation of PPOS’s into SP’s should follow the demand forecast model, as currently happens. Also, given that the orders and the demand forecast evolve during the planning horizon, the disaggregation of a PPOS at a particular week should also consider the evolution of the demand scenario; the impact of the PPOS disaggregation on the possibility to allocate incoming demand or vice-versa should be assessed so that future lateness is minimised.

Table 1. Product hierarchy and alternative routes.

| PPOS ID | SP ID | MA ID | Level 4 (1 to 3) | Level 5 (4 to 10) |
|---------|-------|-------|-----------------|------------------|
| 1       | 1     | 1     | 0.00 1.00 0.00  | 0.00 2.25 0.00  |
| 1       | 1     | 2     | 0.00 0.00 0.00  | 0.00 2.25 0.00  |
| 1       | 1     | 3     | 0.00 1.00 0.00  | 0.00 2.52 2.38  |
| 1       | 1     | 4     | 0.00 1.00 0.00  | 0.00 2.52 2.38  |
| 1       | 1     | 5     | 1.00 0.00 0.00  | 0.97 0.00 0.92  |
| 1       | 1     | 6     | 0.00 1.00 0.00  | 0.97 0.00 0.92  |
| 1       | 1     | 7     | 0.00 0.00 1.00  | 0.00 2.17 2.05  |
| 1       | 1     | 8     | 0.00 1.00 0.00  | 2.31 0.00 2.18  |
| 1       | 1     | 9     | 1.00 0.00 0.00  | 2.05 0.00 1.93  |
| 1       | 1     | 10    | 0.00 0.00 1.00  | 0.54 0.00 0.00  |
| 1       | 1     | 11    | 0.00 1.00 0.00  | 0.80 2.52 0.75  |
| 1       | 1     | 12    | 0.00 0.00 1.00  | 0.97 0.00 0.92  |
The problem addressed in this study lies in the disaggregation of SP’s into MA’s. The further level of disaggregation is excluded from this analysis as the choice of the distribution centres is dictated by the location of the final customers; this decision does not affect the production plan. It is worth noting that the logic developed for assessing the disaggregation of SP’s into MA’s could be extended to the disaggregation of PPOS’s into SP’s should the order management flexibility be considered sufficient to allow SP variations.

3.1. PPOS disaggregation into SP’s and initial solutions

As highlighted before, the PPOS disaggregation into SP’s is exclusively based on historical demand patterns. Due to relevant difficulties in accessing real data for confidentiality reasons, random demand profiles are currently used to generate initial disaggregation solutions. The demand profiles are randomly generated based on realistic assumptions in terms of global demand quantities. Table 2 reports the format used for the demand profile generation. The first three columns report the disaggregation hierarchy for a certain PPOS (as in Table 1). For each MA, at any given week x, the total number of units required is estimated (e.g. 3000 units of MA22 are initially required at week x). A minimum number of units is also specified; this incorporates information on exclusion lists applicable on a particular MA forecast at a given week. In other words, the minimum number of units refers to the units that are constrained to follow the production route associated with the corresponding MA. As an example, 60 units of MA24 must be scheduled on MA24 production route; the remaining 2490 units could be allocated to the alternative routes available for the corresponding SP (e.g. MA22 and MA23). The complete demand profile includes demand forecast for all the MA’s considered in the analysis.

Table 2: Demand profile format.

| PPOS ID | SP ID | MA ID | Total # units | Min # units |
|---------|-------|-------|---------------|-------------|
| 3       | 8     | 22    | 3,000         | 330         |
| 3       | 8     | 23    | 0             | 0           |
| 3       | 8     | 24    | 2,550         | 60          |
| 3       | 9     | 25    | 9,450         | 15          |
| 3       | 9     | 26    | 0             | 0           |

Preliminary analyses on historical data confirm the possibility of deriving demand profiles in a format similar to the one considered in Table 2. Demand profiles are generated for both the PPOS to be disaggregated and the future demand; these profiles are used as initial solutions for the MA allocation procedure. As regards the PPOS profile, demand forecast is generated at the target week whereas for the future demand, initial disaggregation solutions are generated for the entire planning horizon. The future demand incorporates information on possible incoming orders that have not been considered yet in the production plan.

3.2. MA Allocation Procedure

Once the initial disaggregation solution has been generated, its feasibility is assessed following fundamental capacity allocation steps. The definition of the allocation steps was inspired by the logic followed by the demand planners when manual adjustments to the production plans obtained using automatic disaggregation rules are required. The steps are applied to the MA list provided by the initial disaggregation solution. For allocation purposes, the MA’s are considered in an order based on priorities that can be defined by the demand planners or also derived from the level of confidence of the corresponding demand forecast. Each allocation step is applied to all the MA’s in the ordered list before the consecutive step is considered. The allocation procedure includes the following steps:

1. Allocate the MA’s at the required week following the original MA route;
2. Allocate possible remaining excess units to previous week(s) following the same production route (e.g. same MA) up until the maximum earliness allowed is reached;
3. Separate constrained excess units from unconstrained excess units;
4. Allocate constrained excess units to following weeks (same route/MA will be considered) up until the maximum lateness allowed is reached. Remaining demand will be classified as Min Excess demand.
5. Allocate unconstrained excess units on alternative routes/MA’s at their planned week;
6. Allocate unconstrained excess units on alternative routes/MA’s at previous week(s) up until the maximum earliness allowed is reached;
7. Allocate unconstrained excess units on the original MA route at following week(s) up until the maximum lateness allowed is reached;
8. Allocate unconstrained excess units on alternative MA routes at following week(s) up until the maximum lateness allowed is reached. The remaining unconstrained excess units will be classified as unconstrained excess demand.

Based on the steps above, priority is given to the route initially planned. It is also possible to allocate the demand planned for a week to different weeks based on the capacity available at the facilities in the supply chain; a maximum number of weeks is set for both earliness and lateness.

The capacity allocation logic, that is the way variations in the capacity available due to the allocation of production orders to a certain route area accounted, replicates the logic used in the company’s planning system. According to this logic, the production flow through the supply chain is synchronous; as a consequence the time scale in the capacity planning process can be redefined and considered static. This means that the allocation of production capacity at any bottleneck to a particular order can be referred to the out date.
of that order; as the order progresses in the consecutive stages of the supply chain the out date does not change. It is obvious that the production time will change; however, actual production plans with actual production dates are generated in the short term planning period.

In the original implementation of the allocation procedure, only the PPOS to be disaggregated is considered. This basic implementation assesses the feasibility of the initial disaggregation plan and transforms it from an uncapacitated plan to a capacitated one. At the end of the allocation procedure, the global lateness and earliness, the number of excess units and the capacitated production plan are obtained. The global lateness (or earliness) is calculated as a sum of the number of units \( (x_i) \) allocated to a week \( (i) \) different than the one originally planned \( (k) \) for an order weighted by the entity of the delay (or anticipation):

\[
Lateness = \sum \max\{0, x_i(i-k)\}
\]

where \( i \) varies across the entire planning horizon.

The production plan generated by the planning algorithm is presented in the format reported in Table 3. The first five columns summarise the demand profile; the order ID (first column) is an identifier for a particular MA request, then the MA ID, the total number of units and the minimum (or constrained) number of units as reported in Table 2 follow; finally, the planned week, that is the week at which the MA order is initially placed, is reported. The following three columns contain the disaggregation solution generated in the first successful allocation attempt for an order: the MA ID is reported as this could prove different from the original one due to the choice of alternative routes, the number of allocated units for that allocation attempt and the week at which the number of allocated units will be produced. An allocation attempt corresponds with a successful allocation step; hence, several attempts could be reported in the resulting production plan, provided that excess units after the first allocation step exist. As an example, in Table 3 all the orders initially planned for week 6 have been allocated to week 7 in the first attempt; of all these orders, except order ID 73, it is interesting noting that the allocation to week 7 has been performed in two different attempts. The first attempt allocates the minimum number of units (e.g. Allocation Step 4) and the second one allocates the unconstrained number of units (e.g. Allocation Step 7). Moreover, for order ID 75, it is evident that the second allocation attempt corresponds with allocation step 5; this means that sufficient capacity was found at the initially planned week for order ID 75 when alternative routes were considered.

4. Solution Variants

Variants of the basic implementation logic have been developed in order to evaluate the impact of incoming future demand on the PPOS disaggregation. In these variants, the future demand is allocated first so that the PPOS disaggregation is influenced by the remaining capacity available. This means that the choice of the production routes for the current PPOS is made so that sufficient capacity is left for accommodating future orders, especially those that are constrained to specific routes; hence, the flexibility of the PPOS allocation process is exploited at its maximum extent. The first variant involving the future demand (PPOS and Future demand disaggregation) simply applies the allocation steps to the future demand forecasted for the PPOS’ target week. Then, the PPOS disaggregation is performed. However, as earliness and lateness are allowed, the production plan at other weeks will be affected by the demand disaggregation at the target week. This will cause possible consequences on the demand disaggregation at different weeks as the capacity available for the associated demand will be reduced. In order to overcome this limit the following allocation strategies have been developed. These strategies are exclusively applied to the disaggregation of the future demand; the PPOS disaggregation always refers to the target week as this is the objective of the analysis.

Table 3. Output production plan format for future demand.

| Initial Future Demand Disaggregation | Allocation Attempt No. 1 | Allocation Attempt No. 2 |
|--------------------------------------|--------------------------|--------------------------|
| Order Id | MA ID | Total # Units | Min # Units | Planned Week | MA ID | # Allocated Units | Week | MA ID | # Allocated Units | Week |
| 72 | 5 | 14116 | 1412 | 6 | 5 | 1412 | 7 | 5 | 12704 | 7 |
| 73 | 38 | 2823 | 0 | 6 | 38 | 2823 | 7 |
| 74 | 9 | 22586 | 3388 | 6 | 9 | 3388 | 7 | 9 | 19198 | 7 |
| 75 | 33 | 8470 | 1694 | 6 | 33 | 1694 | 7 | 33 | 6776 | 6 |
| 76 | 17 | 22586 | 2823 | 6 | 17 | 2823 | 7 | 17 | 19763 | 7 |
| 77 | 6 | 8470 | 1412 | 6 | 6 | 1412 | 7 | 6 | 7058 | 7 |
| 78 | 7 | 73028 | 7303 | 7 | 7 | 73028 | 7 |
| 79 | 5 | 82157 | 2739 | 7 | 5 | 82157 | 7 |
| 80 | 28 | 73028 | 14606 | 7 | 28 | 73028 | 7 |
| 81 | 22 | 36514 | 0 | 7 | 22 | 36514 | 7 |
| 82 | 27 | 82157 | 6390 | 7 | 27 | 82157 | 7 |
| 83 | 37 | 68464 | 6846 | 7 | 37 | 58760 | 7 | 37 | 9704 | 8 |
It is worth noting that this first implementation of both PPOS and future demand disaggregation proves more computational efficient than the following ones; it also provides similar results provided that the capacity available at the target week is sufficient to accommodate the global demand at that week.

The first variant of the PPOS & Future demand disaggregation (e.g. Allocation Strategy 1) applies the allocation steps to the future demand considering all weeks of the planning horizon (Figure 2). The strategy starts by allocating the future demand at the first week of the planning period; orders forecasted for week 1 are isolated and the allocation steps are applied to this demand following the same logic illustrated in Section 3. Once the allocation for the demand at week 1 is completed, the following week is considered; the allocation procedure is repeated for all the consecutive weeks up until the last week of the planning horizon is reached.

The second variant, Allocation strategy 2, modifies the implementation of the allocation steps by considering one step at a time and completing the procedure for all the weeks in the planning horizon before applying the following step (Figure 3). The procedure starts by considering the first allocation step; orders planned for week 1 are considered and the first application step is applied to them. Then, orders planned for the second week are isolated and the first allocation step is implemented; the procedure continues until the first step is applied to orders planned for all the weeks in the planning horizon. Then, the second allocation step is considered and the procedure is iterated starting from the excess units of orders planned for the first week, then the second week, etc...

All the allocations steps are consecutively applied until there is no excess units left for all the orders considered or the last allocation step is completed.

Finally, Allocation Strategy 3 slightly modifies Allocation Strategy 2 by applying sets of allocation steps rather than single steps at each iteration of the procedure (Figure 4). Allocation sets consists of two or more steps conveniently grouped in order to improve the allocation performance and, hence, minimise lateness. As an example, steps 2, 3 and 4 in Section 3.2 are grouped so that precedence is given to the allocation of constrained units. Steps 5 and 6 and steps 7 and 8 form allocation sets 3 and 4, respectively; in this way the possibility of allocating excess units to an earlier (or later) week than the planned week is investigated on both the original and alternative routes before further weeks than the target one are considered.

All the allocation strategies described have been implemented in MATLAB®vR2011. The computational times are very low; allocation strategy 3, which is the most computational expensive, is completed in times of the order of milliseconds for an allocation problem instance of 40 MA’s and 10 planning weeks, that is 400 MA’s to allocate. However, as Excel® files are used to store input and output data, the interfacing times prove quite slow in comparison (~20 seconds). Verification experiments were run on a 2.6 GHz processor.

4.1 Scenario analyses

Using the strategies described above, scenario analyses can be performed. Several future demand profiles can be generated and the chosen allocation strategy applied to the various scenarios so that corresponding production plans can be obtained and compared. The PPOS to be disaggregated and its associated initial solution will remain the same throughout the scenarios analysed. The logic behind the scenario analysis is to prove the robustness of a PPOS disaggregation plan with respect to future incoming orders’ variations. The solutions obtained for the scenarios are ranked based on the probability associated with the demand scenario. If the PPOS
disaggregation plan does not vary with respect to the scenarios, evidence is provided that the disaggregation solution is optimal and robust as it will not affect the allocation of future incoming orders. On the contrary, when the PPOS plan varies for the different scenarios, the solution obtained is only sub-optimal and it might affect future allocation capability. In this case, the disaggregation plan obtained for the most probable scenario should be considered.

4.2. Strategies comparison

As anticipated in the introduction section, realistic experimental plans could not be developed due to the lack of real data available; hence, practical and significant results can not be shown. However, verification experiments were performed to prove the correctness of the allocation procedures and based on the results obtained some considerations on the performances of the different strategies can be derived.

When allocation priority is given to orders planned for the first weeks of the planning period, allocation strategy 1 should be applied. Indeed, in strategy 1, demand planned for the initial weeks is fully allocated before demand planned for later weeks is considered. Giving priority to the demand associated with the first weeks can be justified from a planning perspective as the orders forecasted for the initial weeks have a higher likelihood to be converted into actual orders. Moreover, there is less flexibility associated with the orders planned for the first weeks because the initial weeks are closer to the definitive production plans and delays involving the corresponding orders are difficult to be recovered by means of plans’ variations. However, time-based priority, that is priority given to demand corresponding with weeks considered in an ascending order, can penalise the realisation of the initial demand disaggregation plan. In this case, allocation strategy 2 should be considered; in this strategy, allocation priority is given to orders planned for a certain week as the first allocation step (Section 3.2) is repeatedly applied for all the orders starting from week 1 to the final week. In the consecutive allocation steps, allocation priority to orders of the first weeks is still maintained as earliness, alternative routes and lateness are progressively considered starting from the orders planned for week 1. This strategy represents a good compromise between time-based priorities and order-based preferences. Finally, allocation strategy 3 expands allocation strategy 2 in order to avoid unnecessary delays or excessive anticipation of orders with respect to the associated target week. Order-based priorities are still considered as the first allocation set corresponds with the first allocation step; likewise, the time-based priority is respected in the sense that production orders are considered based on time ascending order. However, in terms of earliness and lateness, the routing flexibility is better exploited as possible alternative routes are explored before other weeks are considered. Obviously, this approach would not be preferable if the demand planner decides to implement the initial disaggregation plan as much as possible (e.g. consider the same routes initially chosen). Based on the verification results, allocation strategy 3 proves the most effective in generating production plans with minimum lateness. However, practical considerations on the possibility to integrate the strategies proposed into the real planning system and results obtained from experimental plans developed using real scenarios should be taken into account in order to identify the best strategy. This will be done when access to real data will be made available.

5. Discrete Event Simulation Model

The capacity allocation logic described in Section 3.2 reveals that the progression of an order through the supply chain is not associated with any progression in time as the capacity available at a facility is referred to the production out date. As a consequence, the production flow through the system cannot be modelled using discrete events triggered by time. Being this industrial case, a pilot case for an ongoing ambitious research project whose objective is to provide discrete event simulation-based decision support tools, the mid-term production planning problem investigated here has been also solved using a discrete event simulation approach. Specifically, a process-oriented simulation approach has been used and implemented in SimPy2. In process-oriented discrete event simulation, processes are used to describe how the system should evolve. Each process can be considered as a living object characterised by event methods that specify how each object should react to each event in the simulation. An event agenda is kept; for each event appropriate process methods are called so that appropriate actions are taken. This approach proves generally more intuitive and easy to implement than the more common event-based approach for which events are considered one at the time and their processing can generate further events to be added to the event agenda. In the SimPy implementation of the process-oriented approach, the “yield” statement plays a fundamental role. “yield” statements function as return statements as they give back control to the SimPy run-time system; however, unlike a return statement, when a yield statement is called the calling method will be resumed at the last yield processed rather than at the beginning of the method. Only generator methods, which are the main methods of a process object, can call yield statements; any other object can have methods that specify the object behaviour, however, these methods do not generate further events.

Due to the nature of the problem investigated here, the classical implementation of the process-oriented discrete event simulation approach is modified so that the simulation run-time does not correspond with the simulated time. Indeed, time does not trigger the realisation of production-related events, such as the progression of an order to the next production stage; on the contrary, the events consists of elementary allocation phases whose completion triggers the realisation of the following phase. A hierarchical approach has been used to model the problem: the principal processes considered in their hierarchical bottom-up order are:

- **Capacity allocation:** this process verifies whether the capacity required for the allocation of a certain number of units on a particular route is available at the required
facilities. If the allocation is successful, the facility capacity is updated and the associated order is no more considered; if the allocation is partially successful, the remaining capacity and the excess number of units is returned. If no allocation is performed, no change is made to either capacity or quantity of units to be processed.

- **Allocation procedure:** this process models the various steps of an allocation strategy. Instances of the capacity allocation process are opportunistically created as the procedure progresses; the list of orders that should undergo the capacity allocation verification is created and passed to the capacity allocation process. Information on the current allocation week and the possibility of considering alternative routes are also given to the capacity allocation process.

- **Allocation management:** this process governs the generation of allocation procedure instances for both the future demand and the PPOS to be disaggregated. It represents the highest hierarchical level.

Each step of the generator methods of the processes above correspond with a yield statement. The progression of events in the generators is also regulated by “yield waitevent” statements that compel a method to wait for the realisation of an event before the following action is taken. In this case, as an example, the triggering events consist of the completion of the capacity allocation process, an allocation step in the allocation procedure, the completion of the allocation procedure, etc…

Orders are modelled as static objects characterised by several attributes which contain information about the number of total and constrained units, the planned week, the MA and order identifiers.

Several experiments have been run to validate the DES model against the planning algorithm model. The results obtained prove that the two approaches deliver the same results. Moreover, the SimPy model proves much faster in terms of time needed to import and export data from/to Excel; for the same problem instance considered in Section 4, the solution was generated and available in the output file in 0.2 seconds.

6. Conclusions

In this study, the mid-term planning problem has been investigated for a real supply chain characterised by high routing flexibility. Simulation-based decision support tools have been developed to support the demand planners in the complex task of disaggregating family type forecast demand into finer granularity products for which the production route is established. In the real planning system where disaggregation decisions are exclusively based on both historical demand patterns and applicable routing constrains; this generates uncapacitated production plans for which significant orders’ delivery delays can be experienced. The solutions developed here integrate information on the capacity available in the supply chain and assess the impact of future demand scenarios so that the resulting lateness is minimised.

Historical demand patterns are used to generate initial disaggregation solutions; this is necessary as the first level of product disaggregation proves less flexible and governed by the customers’ preferences. Routing flexibility is exploited at the second disaggregation level in order to maximise the capacity utilisation and avoid unnecessary lateness. The solutions developed are based on fundamental allocation steps inspired by the allocation logic used in the real systems. Variants to the basic allocation procedure have been developed so that time-based and order-based allocation priority could be considered. The study illustrated in this paper is still work-in-progress and experimental results based on real data are not yet available. However, the experiments run to verify the planning algorithm highlighted supported a theoretical comparison of the allocation strategies described. Finally, the results obtained using the planning algorithm have been replicated using a process-oriented DES approach. In the DES model developed, events are not triggered by time progression but by the realisation of controlling events. Significant computational efficiency improvements have been observed for the DES approach as the time needed to import and export simulation data from Excel files has significantly decreased with respect to the planning algorithm implementation. The DES model treats time as an object attribute.

In the near future, the strategies performance will be tested using real data; moreover, the demand planners will review the strategies’ logic in order to identify the one that proves more suitable to be integrated in the real planning system.

Acknowledgments

The research leading to these results has received funding from the European Union Seventh Framework Programme (FP7-2012-NMP-ICT-FoF) under grant agreement n° 314364.

References

[1] Stevenson, M., Spring, M. Flexibility from a supply chain perspective: definition and review. International Journal of Operations & Production Management; 2007, 27:7, p.685-713.

[2] Gerwin, D. Manufacturing flexibility: a strategic perspective. Management Science; 1993, 39:4, p.398-410.

[3] Soon, Q.H., Udin Z.M. Supply chain management from the perspective of value chain flexibility: an exploratory study. Journal of Manufacturing Technology Management; 2011, 22:4, p.506-526.

[4] Chan, F.T. Performance measurement in a supply chain. The International Journal of Advanced Manufacturing Technology; 2003, 21:7, p.534-548.

[5] Gupta, J.N., Tunc, E.A. Schedules for a two-stage hybrid flows with parallel machines at the stage second. The International Journal of Production Research; 1991, 29:7, p.1489-1502.

[6] Linn, R., Zhang, W. Hybrid flow shop scheduling: a survey. Comput Ind Eng; 1999, 37:1, p.57-61.

[7] Ribas, I., Leisten, R., Framiñan, J.M. Review and classification of hybrid flow shop scheduling problems from a production system and a solutions procedure perspective. Comput Oper Res; 2010, 37:8, p.1439-1454.

[8] Terzi, S., Cavaliere, S. Simulation in the supply chain context: a survey. Computers in Industry; 2004, 53:1, p.3-16.

[9] Geraghty, J., Heavey, C. A review and comparison of hybrid and pull-type production control strategies. OR Spectrum; 2005, 27:2-3, p.435-457.