Proceedings of the 2016 Winter Simulation Conference
T. M. K. Roeder, P. I. Frazier, R. Szechtman, E. Zhou, T. Huschka, and S. E. Chick, eds.

FRAMEWORK FOR STANDARDIZATION OF SIMULATION INTEGRATED PRODUCTION PLANNING

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ABSTRACT

Production planning is a complex problem that is typically decomposed into decisions carried out at different control levels. The various methods used for production planning often assume a static environment, therefore, the plans developed may not be feasible when shop floor events change dynamically. In such an operating environment, a system simulation model updated with real-time data can be used to validate a proposed plan. In this paper, we propose a framework to evaluate and validate the feasibility of high-level production plans using a simulation model at a lower level thereby providing a base for improving the upper level plan. The idea is demonstrated with an assembly plant where the aggregate plan is evaluated using discrete event simulation (DES) of shop floor operations with resources allocated according to constraints imposed by the aggregate plan. We also discuss standardized integration interfaces required between simulations and production planning tools.

1 INTRODUCTION

Managing a manufacturing system to meet production objectives in face of dynamic events and changing priorities is a major challenge. Simulation models are often used to evaluate and generate production plans and schedules to achieve those objectives. Indeed, the vision of smart manufacturing systems includes that simulation will be pervasive and integrated throughout the multiple layers of operation and decision-making (AIChE 2012). However, such models specifically for production planning, are not yet ubiquitous through the multiple control levels.

Production plans affect many other functions in the organization because they are the basis for acquiring raw materials and establishing resource requirements such as manpower, tooling, and machine capacity. Bitran et al. (1989) identified three decision levels into which the production planning problem can be decomposed: aggregate, scheduling, and dispatching. Aggregate planning relies on nominal production rates to determine capacity requirements during each period over the planning horizon. Typically, optimization formulations are applied to this problem. Scheduling determines production quantities for each product family during a period within capacity already set by the aggregate plan. Shop floor control determines actual resource and routing of production lots, precise timing, and dispatching procedures.

Methods such as dynamic programming, expert systems, priority rules, and heuristics have been applied to scheduling and control problems.

Decomposing production planning into sub-problems simplifies the process of deriving a workable problem that is solved at each level. However, as noted by White (2012), changes in factors such as product mix, equipment status, and staffing imply that originally derived plans may not be accomplished by prevailing shop floor capacity. Tools such as simulations evaluate the impact of decisions and feedback within different production planning levels. Existing production systems such as CONWIP (CONstant Work In Process) help control work-in-progress but would need look-ahead capability and feedback that includes simulation output to an aggregate level (Spearman 1990).

In this paper we propose a framework to evaluate feasibility of high-level production plans using a simulation model of the system at a lower level. The results of simulation model from the look-ahead results are used iteratively to generate a new upper level plan. The idea is demonstrated in an assembly plant where the aggregate plan is evaluated using discrete event simulation (DES) of shop floor operations with the schedule of resources are allocated to production activities according to constraint imposed by the aggregate plan. Simulation is used in three contexts: (1) as a surrogate for a real life plant, (2) as a look-ahead evaluation of plans that uses shop floor status, and (3) as feedback to generate a better plan by improving on a previous plan.

The tools used in this demonstration, as with most commercial systems, are often not interoperable. Therefore, interfaces to integrate simulation and scheduling tools are major focuses of this paper. The rest of the paper is organized as follows. Section 2 gives an overview of related work and shows how current work differs from previous research. Section 3 discusses relevant standardization needs. Section 4 presents the proposed framework. Section 5 describes a case study used to demonstrate the framework. Section 6 presents the final discussion and conclusion.

2 RELATED WORK

Common production management systems are Enterprise Resource Planning (ERP) for aggregate planning and Manufacturing Execution Systems (MES) for scheduling and control. There are also advanced planning and scheduling (APS) that are designed to be more adaptable in a changing environment. The success of production planning depends on coordinating actions at different control levels. Therefore, integrating simulations that incorporate stochastic shop floor elements can not only increase realism but also improve coordination and performance of plans.

Simulation methods have been used for production planning for many years (Drake and Smith 1996). More recently, a survey by Negahban and Smith (2014) revealed that simulations are still widely used for validating production plans, schedules, operating policies, and real-time control. The use of simulation in combination with scheduling tools produces a synergistic effect that results in greater productivity. A few citations from various types of manufacturing environments follow.

Vasudevan (et al. 2008) report a practical application where schedules generate input parameters to simulation for production validation in drill collar manufacturing. In semiconductor manufacturing, Bang and Kim (2010) use a two-level hierarchical method in which aggregate production decisions are formulated as linear programming while priority rule-based scheduling methods are used for lower level shop floor operations. Both are evaluated using DES to obtain a feasible plan iteratively. In job-shop scheduling, Kulkarni and Venkateswaran (2014) develop an iterative approach to obtain optimality by using simulation to iteratively test feasibility of solutions from a linear program. Battista et al. (2011) use stochastic simulation models to investigate effects of ERP decisions (e.g., lot sizing criteria) and other random system variables. Moon and Phatak (2005) determine a bi-directional feedback between a stochastic simulation and ERP to improve accuracy in prediction of order completion times. Lastly, Hatim et al. (2015) develop a methodology for simultaneously optimizing production plans and sustainability.

The above reported citations show that production plans can be enhanced by simulation. However, most of these researches were done on piece-meal basis. While Venkateswaran and Son (2005), and Helal (2008) developed frameworks for integrated multi-method simulations, a framework that links aggregate plans, production planning, and shop floor control activities is lacking. This paper develops and demonstrates the application of such a framework.

3 FRAMEWORK: CONCEPT AND PROCEDURE

Figure 1 shows a conceptual top-down approach where levels are consistent with the ISA-95 standard (ANSI 2013). Simulations are used for (1) generating a plan and (2) evaluating feasibility of plans passed from a higher level. To generate a plan at the aggregate level, simulation helps investigate the stability of an original plan by testing how sensitive it would be to changes in operating environment. At the operational level, simulation ensures a good schedule by investigating flexibility should unforeseen events occur. At the dispatching and control level, simulation is used to determine if the plan and schedule can be executed using current resources status. The scope of this paper is on the second purpose, i.e., feasibility evaluation with plans and schedules initially produced by analytical formulations, and genetic and heuristic algorithms.

When a plan is passed from aggregate level, the operational level develops a schedule to execute the plan. This schedule is simulated at the operational level to evaluate feasibility and perform any revisions that may be needed. Once a valid schedule is obtained, it is passed to dispatching and control at the shop level where there are two types of plan revisions that may be needed. Minor or short term changes involve only the schedule while major deviations require aggregate plan revision, as Figure 2 shows. The performance of current plan is fed back to improve likelihood that the next iterations of planning and resource allocations would be executed on the shop floor. The simulation models only need to be executed when new plans are needed and do not necessarily have to be run concurrently.

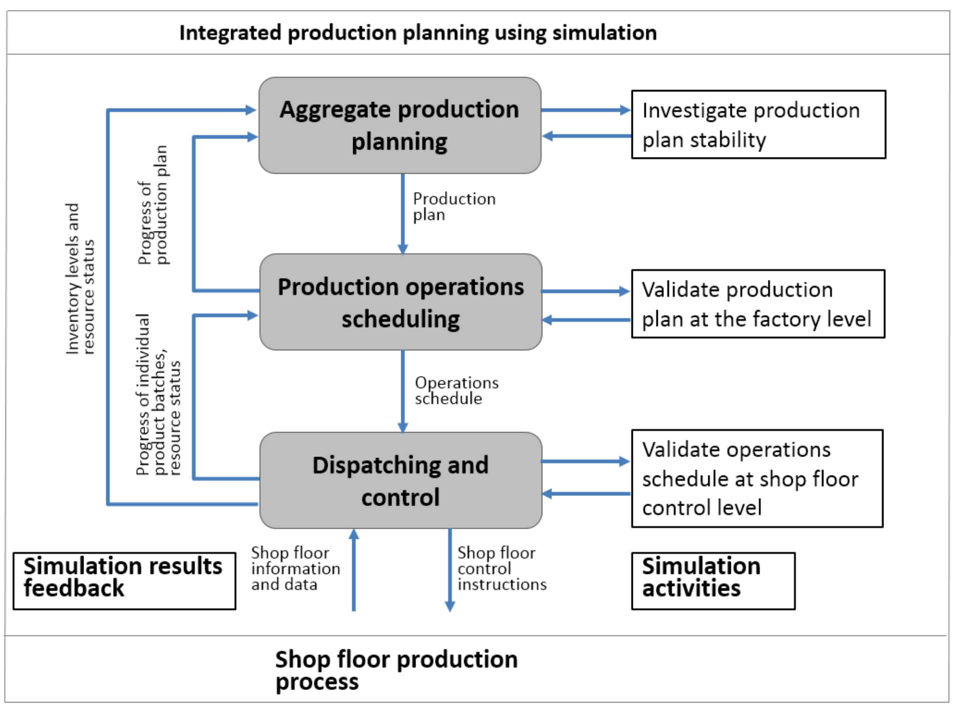

Figure 1. Simulation result feedback for integrated production planning.

4 DEMONSTRATION

The framework is demonstrated with a production line using two of three planning levels of the framework: aggregate and operational. The production planning is consistent with ISA-95 as follows: aggregation of production quantities, sequencing of multiple product batches, allocation of resources, data collection from resources. Figure 2 illustrates the procedure. Aggregate planning determines production quantities and corresponding production capacity during each period over the planning horizon based on (1) the projected demand and (2) the relationship between production level and number of workers on the line. This capacity changes by hiring or firing workers at the beginning of each period. Operational planning allocates resources or production capacity on the production line on a shift by shift basis. While the initial formulation is deterministic, it is with a stochastic simulation that investigations of schedule feasibility are carried out and from which feedback of system performance are obtained. The role of simulation is to evaluate aggregate plan using simulation of the production line and feedback simulation run result to scheduling and aggregate planning.

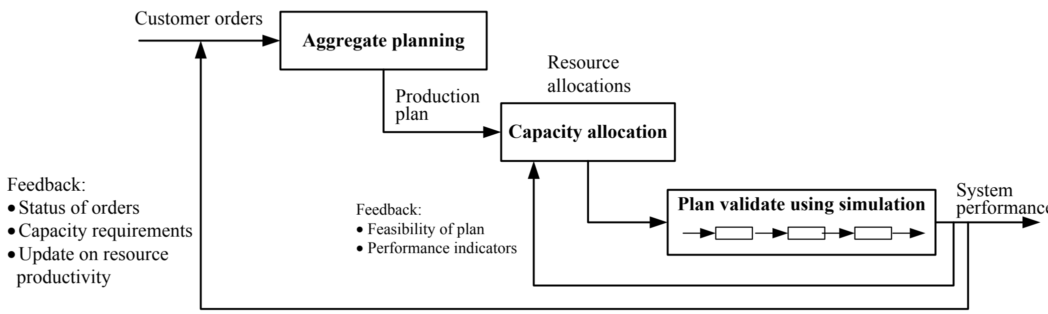

Figure 2: Activities for simulation supported production planning.

4.1 Aggregate Planning Model

Common objectives for formulating the problem as a linear programming model include:

- Minimize late orders
- Minimize work-in-progress inventory costs
- Maximize bottleneck resource utilization
- Minimize total cost assignment of production lots to periods over the planning horizon

In this paper, we focus on the last objective on the list in our formulation. The costs are combined production, production smoothing, and inventory costs. If i and t are the indexes of products {1, 2,…, N} and periods {1,2,..., T} respectively, the objective function is represented as follows.

$$\text{Minimize } \left(\sum_{t=1}^{T}\sum_{i=1}^{N} P_{it}X_{it} + C_H\sum_{t=1}^{T} R_t + C_F\sum_{t=1}^{T} F_t + \sum_{t=1}^{T}\sum_{i=1}^{N} H_{it}I_{it}^{+} + \sum_{t=1}^{T}\sum_{i=1}^{N} S_{it}I_{it}^{-}\right) \tag{1}$$

P_{it} is production cost, C_H is hiring cost per worker, C_F is firing cost per worker, H_{it} is inventory holding cost, and S_{it} is shortage cost per unit. X_{it} is the number of units produced, R_t is the number of workers hired while F_t is the number of workers fired at the beginning of a period T, I_{it} is the inventory of product *i* at end of period *T*; I_{it}^{+} is the positive inventory, and I_{it}^{-} is the negative inventory.

W_{it} is the number of workers on the line during the period, X_{it} is a function of W_{it}. K_{it} is a constant that defines the relationship as shown in equation (2). Production, demand, and inventory are balanced using equation (3) while conservation of workforce from period to period is indicted in equation (4). Equation (5) is for inventory. Equation (6) shows constraints on minimum number of workers on the production line to operate as well as the maximum possible labor capacity. These result in sets of constrains below:

$X_{it} = f(W_{it})$, for linear $X_{it} = K_{it}W_{it} + C$ (a constant) (2)

$I_{it} = I_{it-1} + X_{it} - D_{it}$ (3)

$W_t = W_{t-1} + R_t - F_t$ (4)

$I_{it} = I_{it}^{+} - I_{it}^{-}$ (5)

$W_{min} \leq W_t \leq W_{max} \quad \forall\ i, t$ (7)

4.2 Operational Planning – Shop Floor Resources Allocation

The scheduling and allocation of resources on the shop floor depends on the nature of the production system. In this demonstration, we consider production of a single product or product mix being assembled continuously without interruption. Each workstation has a production rate depending on the number of operators allocated. Buffers vary as a linear function of time and of the production rates of the workstations immediately upstream and downstream. Thus, given a set of initial buffer sizes at the beginning of a shift, a set of target buffer sizes required by the end of the shift, and a production target of specific product types by the end of the shift, the required processing rates at each workstation can be computed.

Mathematical formulation:
This formulation assumes the following:

- There are no shortages of incoming raw materials
- Process times are deterministic and production rate is proportional to number of operators
- The materials handling time between workstations has no effect on production

Let buffers (b) and workstations (w) be arranged in the series, b_1, w_1, b_2, w_2,.....,b_i, w_i,.....b_{n-1}, w_{n-1}, b_n as shown in Figure 3.

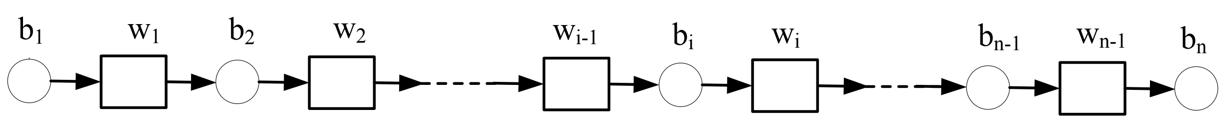

Figure 3: Flow line manufacturing.

If workstation i-1 feeds buffer i at rate r_{i-1} while being depleted at a rate r_i , the size of buffer i at time t, $b_i(t)$, is related to the size of the buffer at time 0, $b_i(0)$ by the equation (Kibira 1995):

$$b_i(t) = b_i(0) + (r_{i-1} - r_i)t \quad (7)$$

The finished product at time t, b_n, which also forms the boundary condition, is

$$b_n(t) = r_{n-1}t \quad (8)$$

Manufacturing systems are often operated with scheduled interruptions due to maintenance or convenience breaks. Let us consider workstation *i* being interrupted between times t_1 and t_2 such that this workstation can only operate at a rate r_{iB} (lower than normal) during this period. If the work rate is r_{i1} before and r_{i2} after the interruption, the state equations for buffer sizes immediately upstream and downstream of the workstation *i* are:

$$b_i(t) = b_i(0) + (r_{i-1} - r_{i1})t \quad (9)$$

$$b_{i+1}(t) = b_{i+1}(0) + (r_{i1} - r_{i+1})t \text{ for } t \leq t_1 \quad (10)$$

$$b_i(t) = b_i(t_1) + (r_{i-1} - r_{iB})t \quad (11)$$

$$b_{i+1}(t) = b_{i+1}(t_1) + (r_{iB} - r_{i+1})t \qquad \text{for } t_1 < t < t_2 \quad (12)$$

$$b_i(t) = b_i(t_2) + (r_{i-1} - r_{i2})(t - t_2) \quad (13)$$

$$b_{i+1}(t) = b_{i+1}(t_2) + (r_{i2} - r_{i+1})(t - t_2) \quad \text{for} \quad t \geq t_2 \tag{14}$$

The processing rates at workstations take on values corresponding to a whole number of operators. These rates are slightly different from those originally computed. If v_i is the number of operators at workstation *i*, the buffer size for a downstream workstation at time t is given by:

$$b_{i+1}(t) = b_{i+1}(t_0) + (v_i / p_i - v_{i+1} / p_{i+1})t \tag{15}$$

Some computed buffers may be negative. To obtain actual values, do as follows: If $b_{i+1}(t) < 0$ then reduce $b_{i+2}(t)$ by the absolute value of $b_{i+1}(t)$ and set $b_{i+1}(t) = 0$. Repeat until no negative buffer values.

4.3 Implementation Scenario

The manufacturing case scenario is of a standard telephone assembly facility schematically represented in Figure 4. The system data and demand over the next six periods are shown in Tables 1 and 2 respectively. Assumptions and policies are:

- Products have the same constant K_{it} but may have different period
- Plant operates 5 days/week, 2 shifts/d, 8.5 h. (510 min) shift; and 15 min and 30 min breaks
- The costs do not differ from period to period over the planning horizon, i.e., production cost element is removed from objective equation
- There are no shortages of raw materials including inserted components
- The production rate is directly proportional to the number of operators allocated
- Labor has flexible skills
- Six periods into the future are considered

Table 1: System operational data.

Core production (P_{core})	18 900/week
Core number of workers (W_c)	38
Maximum number of workers (W_{max})	50
Cost of hiring a worker (C_H)	$1000
Cost of firing a worker (C_F)	$2000
Inventory carrying cost (C_I)	$80/week
Inventory shortage cost (C_S)	$160/week
Production units per extra worker (K_t)	400/week

Table 2: Demand for six periods.

Period	Demand
1	26 500
2	17 600
3	22 500
4	16 500
5	21 500
6	24 700

Table 3: The optimal solution from LINGO.

Period	Hired	Fired	Workers in the plant	Throughput

1	12	0	50	22500
2	0	3	47	21600
3	3	0	50	22500
4	0	12	38	18900
5	8	0	46	21300
6	4	0	50	22500

Data from Tables 1 and 2 is input into equation (1) to equation (6) and solved using LINGO for linear programming. The optimal solution in Table 3 shows the number of workers that need to be in the plant each period to provide capacity for the planned throughput. Plant starts 38 workers from previous period.

4.4 The Simulation Model

Figure 4 shows the organization of resources and process operations on the production floor. The initial process is the automatic insertion of about 90 % of the components into a printed circuit board. The final process is where the phone and handsets are packed in a box. There is storage space for work-in-progress buffers at each workstation. Conveyor segments link the various workstations. The model incorporating system variability such as stochastic process times and random breakdowns was developed using the AnyLogic simulation software. Using production capacity from aggregate planning and distribution on the shop floor, the model was run for ten consecutive shifts representing a weekly operation.

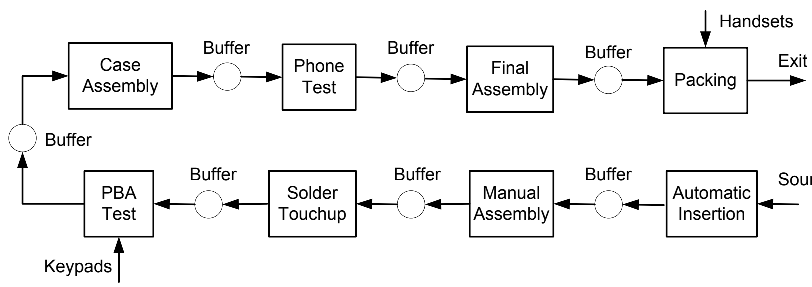

Figure 4: The manufacturing process.

4.5 Results

The production plan, as per the values in Table 3, was used for assigning resources among process steps on the production line using the system of equation (7) to equation (14). Note that allocations at a workstation may be different after a scheduled break. As such, the stochastic nature of the process may result in the number of workers as computed by the capacity allocation not being equal to the pre-planned capacity. In case the total number of workers needed is greater than the planned labor capacity, the solution is to reduce the number of workers starting from those workstations where a reduction least affects throughput until number of workers equals the planned labor capacity. Such cases result in required production quantities being completed sometime after normal shift time. On the other hand, if the number of workers computed is less than the planned labor capacity, operators are added to stations using a reverse policy when selecting stations. Two cases are considered:

- Predetermined capacity and resource allocations throughout the planning period
- Revision of: (1) Allocation in the last section of a shift in response to buffer build-up at some stations and (2) Production capacity at end of each period based on progress of the plan.

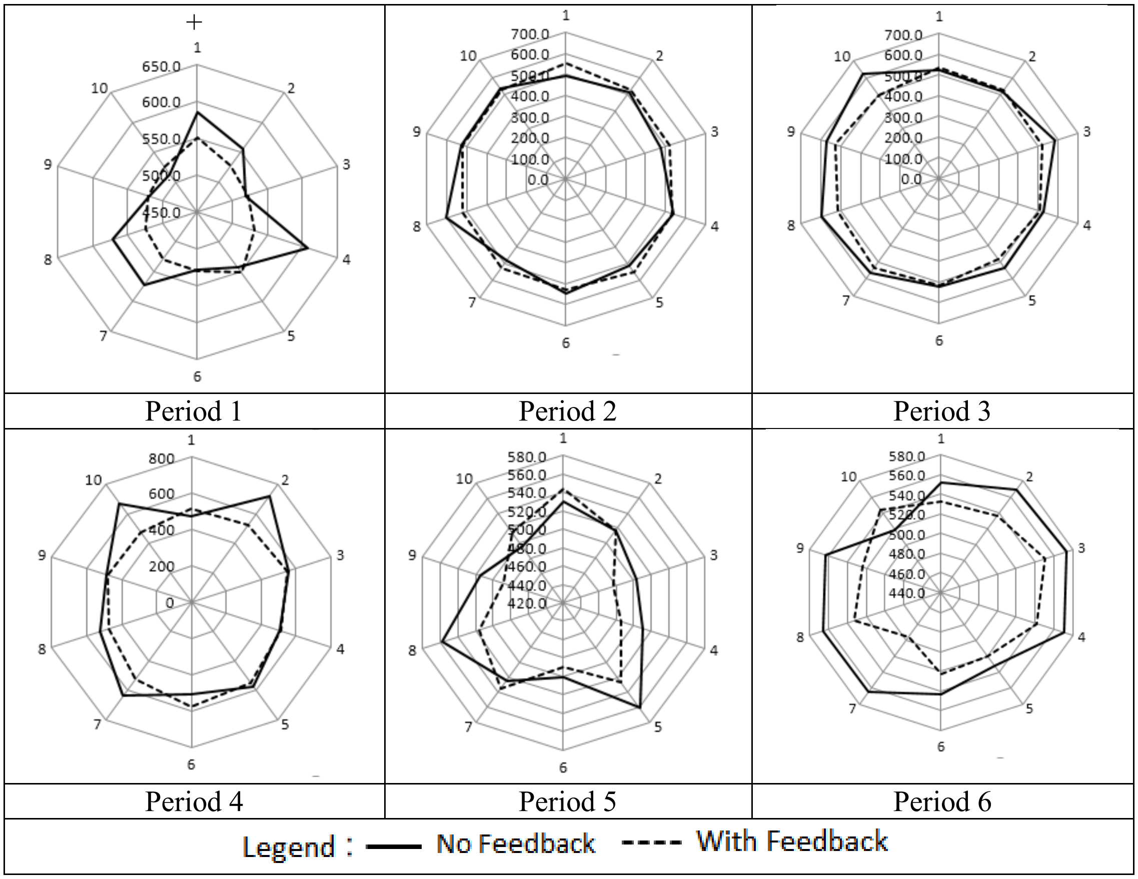

Figure 5: Production quantity completion times in minutes.

Minor revision: These are revisions involving redistribution of operators at workstations during as opposed to a pre-planned labor allocation and determine how long it takes to complete the required production quantity for the shift. The spider charts in Figure 5 show comparison of completion times for the production quantities each shift during the six periods that comprise the planning horizon.

Major revision: This is a revision where (1) number of units completed by the end of each period is compared with required quantity to revise the quantities to produce during the following periods, (2) simulation look-ahead and update on relationship between workers and number of units that can be produced. The constants (K and C) in equation (2) depend on machine status, work in progress, and labor distribution on the line. Using current status, the results of a simulation run are used to estimate new values of K and C, which are used in the problem formulation for subsequent periods to generate a new plan at the beginning of each remaining period. This process results in revised production capacity as Table 4 shows.

Comparison of the performance of revised plans with a predetermined plan shows that revising the production capacity based on progress of execution of orders and updating the relationship between number of workers and production rates results in improved performance. This method is useful in an environment where workers' skills change with time or other changes in the production process.

Table 4: Planned compared with revised capacity.

PERIOD	1	2	3	4	5	6
PLANNED CAPACITY	50	47	50	38	46	50
REVISED CAPACITY	50	50	50	48	48	48

5 INTEGRATION STANDARDS NEEDS

The simulation model was developed in AnyLogic simulation software while aggregate plans were obtained using the LINDO system for linear optimization. Capacity allocation software was also developed in Java and integrated with AnyLogic simulation tool. AnyLogic is based on Java. The output from aggregate planning was translated manually to create a spreadsheet for data input into the simulation model. Similarly, simulation output needs translation for input into optimization formulation. These activities are time consuming and potentially costly. We overview the scope of current tools and integration standards.

5.1 Integration Limitations in Modeling Tools

Companies currently use a variety of simulation and APS tools. However, simulation tools have a low level of interoperability, both amongst themselves and with other manufacturing software applications. Riddick et al. (2010) noted that even when outward interfaces are provided, they are undocumented and/or proprietary. Previous efforts at the National Institute of Standards and Technology (NIST) developed an architecture for integrating simulation models and other manufacturing systems in a distributed environment as an initial step towards standardization (McLean et al. 2000). The interoperability problem still remains. Therefore, the proposed framework needs standards for both developing and interfacing simulations with APS tools through a neutral data exchange format.

5.2 Standards at the Different Decision Levels

A standard would determine the method for generating plans/schedules and data exchanged between and amongst production planning tools and simulations. Lu et al. (2015) surveyed a standards landscape for smart manufacturing along three axes: business process, production system, and product lifecycle. Production planning falls along the business process axis. Although a number of standards are overviewed by the authors, analysis of their scope was not carried out.

We define control levels for integrating production planning functions and simulations, and identify relevant standards according to the ISA-95 standard. Table 5 lists a sample of these standards. At level 4 (the enterprise level) in Table 5, The *ebXML* (Electronic Business XML) uses Extensible Markup Language (XML) to represent the secure exchange of business data (UN/CEFACT and OASIS). ISO 15531-1 standard (MANDATE) addresses information exchanges between software applications according to five identified activities, i.e., planning, scheduling, simulation, control, and execution (ISO 2012; Cutting-Decelle et al. 2007). The Open Applications Group Integration Specification (OAGIS) (OAGi 2014) standard defines business messages for application-to-application for business level integration.

At level 3 (the MOM level), the Business To Manufacturing Markup Language (B2MML) XML schemas are used to implement ISA-95 (MESA 2013). Although control levels are defined from enterprise to machine controls, this standard is emphasized at enterprise level. On the other hand, the Core Manufacturing Simulation Data (CMSD) standard is developed for exchanging data among simulation and other applications, but not for vertical integration (SISO 2012).

At level 2 (the SCADA level), Process Specification Language (PSL) defines a neutral representation for manufacturing processes that supports automated reasoning. And the OPC Unified Architecture (OPC UA) provides a mechanism for moving process data between enterprise-type systems and controls, monitoring devices, and sensors that interact with real world.

At level 1, MTConnect facilitates the organized retrieval of process information from numerically controlled machine tools. MTConnect is an open standard that intends to foster greater interoperability between controls, devices, and applications by publishing data using internet protocol such as XML and Hyper Text Transfer Protocol (HTTP) (MTConnect Part 1, 2011). MTConnect enables a continuous data log for machining. It provides a mechanism for system monitoring, process, and optimization with respect to energy and resources. The information is valuable for analyzing processes and facilities performance (Vijayaraghavan et al. 2008).

Table 5. Relevant standards for different ISA 95 levels.

ISA-95 Level	Relevant Standards
4 (Enterprise)	ebXML, ISO 15531-1, OAGIS
3 (Manufacturing operation management (MOM))	ISO 15531-1, ISA-95/B2MML, CMSD, OAGIS,
2 (Supervisory control and data acquisition (SCADA))	ISO 15531-1, ISA-95/B2MML, CMSD, PSL, OPC-UA
1 (Device)	ISO 15531-1, ISA-95/B2MML, PSL, MTConnect

Table 6. Sample relevant standards and their scopes for integrated production planning.

Standard	Scope
ISA-95 B2MML	Production planning data
CMSD	Production and process data for simulation of manufacturing operations
OAGIS	Production data
ebXML	Production planning data
ISO 15531-1	Production planning data
PSL	Process data
OPC-UA	Real-world data from low-end controllers, sensors, actuators and monitoring devices
MTConnect	Device and machine monitoring data

Table 6 provides scope of reviewed standards, e.g., CMSD can not only represent manufacturing production operations but also specify stochastic characteristics of production processes using probability distributions. These standards facilitate the use of simulation for production planning and integration, especially important in a framework for multi-level production planning tools and simulations.

6 DISCUSSION, CONCLUSION AND FUTURE WORK

This paper proposed and demonstrated a framework for integrating production planning with simulation. Aggregate plan is generated by linear programming formulation with objective of minimizing total costs while the scheduling involves determining the number of workers to allocate to each workstation and is formulated as a flow rate problem. A stochastic simulation model of the system was used to determine feasibility of the plan and rescheduling during a shift in response to deviations from expected production levels due to random events on the shop floor. Further, simulation results are used in developing a new plan at the close of each planning period. Revised plans show improvement in achievement of production goals. The results also help with establishing concurrence in production plans generated by different control levels.

The need for integrating interface between planning/scheduling systems and simulations has been pointed out. Apart from previous work in distributed simulation mentioned, there has been no recent significant research directed to the development of standardized interfaces APS tools and a variety of simulation tools. Further work will include defining and formalizing an appropriate architecture upon which standards can eventually be developed. This will be followed by identifying methodologies for production plan generation at different levels as well as exploration and detailed analysis of standards in the context of production planning. Integrated models of a real-world system will be constructed for production planning according standards such as CMSD and ISA-95 B2MML. Needed extensions to standards to enable modeling simulation and various production data at all control levels will then be identified.

ACKNOWLEDGEMENTS

This effort has been sponsored in part under the cooperative agreement No. 70NANB13H153 between NIST and Morgan State University, and within the Sustainable Production Initiative and the Production Area of Advance at Chalmers. The support is gratefully acknowledged. The work described was funded by the United States Government and is not subject to copyright.

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