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Simulating a Production Facility with an Automated Transport System

Abstract

A model was needed to assess material throughput and validate the conceptual design of a production facility, including equipment lists and layout. The initial desire was to use a commercially available discrete event simulation package. However, the available software was found to be too limited in capability. Database interface software was used to develop autonomous intelligent manufacturing workstations and material transporters.

The initial Extend model used to assess material throughput and develop equipment lists for the pre-conceptual design effort was been upgraded with software add-ons from Simulation Dynamics, Inc. (SDI). Use of the SDI database interface has allowed the upgraded model to include:

1. A material mass balance at any level of detail required by the user, and
2. A transport system model that includes all transport system movements, time delays, and transfers between systems. This model will assist in evaluating transport system capacity, sensitive time delays in the system, and optimal operating strategies.

An additional benefit of using the SDI database interface is dramatically improved run time performance. This allows significantly more runs to be completed to provide better statistics for overall plant performance.

The model has all system and process parameters entered into sub-component accessible tables. All information for the manufactured items and process data is automatically generated and written to database. The standard software is used for the movement of manufactured items between workstations, and for sequence and timing functions. Use of the database permits almost unlimited process control and data collection with an insignificant effect on run time.

Summary

A model was successfully created that assess material throughput and validated the equipment list for the conceptual design of a manufacturing facility. Generic powerful autonomous blocks were developed that can automatically read and write to multiple tables; automatically adjust the manufacturing process based upon the characteristics of the item received; and can be rapidly reconfigured to investigate alternate process characteristics, changes in the number, type, and or location of the workstations; and the characteristics of the transport system.

Preliminary calculations were completed that favorably compare with the original throughput model.

1. Introduction

The flowsheet model is a discrete event manufacturing simulation model of a production process developed with the Extend™ software package. It is used to develop the list of equipment from which facility size and cost estimates are generated.

The basic Extend model: In its initial state, the model tracked the number of individual items through the facility, but not each item's mass. Similarly, recycle material is treated on a unit basis without tracking the specific mass associated with each recycle path.

A newer model using SDI database interface, Excel spreadsheets, more flexible programming, etc. has resulted in: transport system evaluation, more extensive mass balance/inventory capability, faster run times.

The Extend model used to assess material throughput and develop equipment lists for the production facility pre-conceptual design effort has been upgraded with software add-ons from Simulation Dynamics, Inc. (SDI). Use of the SDI database interface has allowed the upgraded model to include:

1. A material mass balance at any level of detail required by the user, and
2. A transport system model that includes all transport system movements, time delays, and transfers between systems. This model will assist in evaluating transport system capacity, sensitive time delays in the system, and optimal operating strategies.

An additional benefit of using the SDI database interface is dramatically improved run time performance. This allows significantly more runs to be completed to provide better statistics for overall plant performance.

2. Initial Model Development

The following developmental areas were addressed in the initial model:

2.1 Mass balance

A mass balance was identified as a high priority item. The utility of the SDI Database interface is apparent, and the ability to track any number of species within the database made further development of the mass balance in the traditional Extend model less attractive. The SDI interface gave the flexibility of tracking any number of components through the system by simply defining another column in the database and adding the necessary balance equations. In addition, tracking the materials through database manipulations proved to be far more time and data storage efficient than carrying the necessary parameters as item attributes in a conventional Extend construct. The reduction in run time was dramatic, making the calculation of meaningful run statistics possible.

The only negative aspect of using the database interface to track mass balances was that the model was closely coupled with the transport system model development, so completing the mass balance calculations was delayed until the transport system logic was completed. As described below, a simple, single-track version of the transport system model was completed and proved to be very fast running. The effort to extend that model is still underway, so the final mass balance calculations have not yet been completed, although the equations necessary to perform those calculations are already in place in the model.

2.2 Transport System modeling

The ability of the internal transport system to support material movement within the manufacturing plant is critical to the successful operation of a facility. The equipment lists generated assumed that a transport system can be designed to keep material moving freely within the plant and not become a bottleneck itself. This was accomplished with the initial model by adding a nominal time delay on many of the specific manufacturing processes to accommodate the requirement to move the work piece. However, this approach was only considered a rough approximation, since it provides neither the accuracy nor the flexibility required to demonstrate the characteristics of a particular transport system design.

There are two aspects of transport system design that can be handled well with software. Each requires a different modeling package. An analysis that can be reduced to the availability of a transport carrier and the time needed to move a package from one location to another can be handled efficiently with database manipulations available through Extend and SDI Industry Pro. These tools have been used to develop a flexible and efficient model of material transport in the foundry section of the production facility.

The Extend model of the foundry was modified to take advantage of the database capabilities of SDI Industry Pro. A sketch of the model is shown in Figure 4. It consists of two fundamental models, with two special models added for input and output. One principal module is a workstation. This is a generalized Extend entity developed to represent any workstation in the facility. It draws all input and output characteristics from tables in a database. The database was developed to provide workstation information in a convenient format that is both easy to read and modify for simulating different operating conditions or layouts. The other principal module is a generalized transporter. It can be used as the transporting mechanism on any given transport system within the plant. It, too, reads its characteristics from tables in the database.

The layout shown in Figure 4 represents two manufacturing lines in the foundry with workstations numbered according to their location in the plant. Movement of material throughout the facility, as well as tracking of process steps, mass inventories, and transport carrier locations is accommodated through the database interface. To understand this process, it is first necessary to discuss the structure of the database. This will be introduced in the next item and discussed in detail in the Transport System Model section.

2.3 Data base interface.

The addition of a database-driven input and output interface was important for two reasons. The first is that data input and output records had to be moved to a more accessible location than the dialog boxes included with traditional Extend modules. While there was no computational difference between entering data through the Extend dialog boxes or using a database, there was a significant difference in the ability to modify input and record the parameters used for a particular analysis. Through the use of add-on software from Simulation Dynamics, Inc., SDI Industry™, all input to and output from the model could be recorded in an Excel spreadsheet. This made the task of modifying input for sensitivity calculations, recording both input and output from the calculations, and completing QA documentation far easier than with Extend alone.

The second reason for implementing the database interface was to facilitate the modeling of the transport system. While a model could probably have been developed using traditional Extend modules, the speed and flexibility afforded through the SDI database interface was so dramatic that continuing development with the existing Extend model could not be justified. Through the use of the database, a model has been developed which allows complete flexibility in locating workstations, assigning specific operations and operational characteristics to each, tracking individual items throughout the system including masses of any number of components and constituents, and calculating all transport operations associated with the movement of those items. At the same time, the run time associated with tracking all this information is far shorter than an Extend model which includes far less detail.

The newly developed model utilizing the database features of SDI Industry Pro will be discussed in detail below.

3. Manufacturing Models

3.1 Extend Manufacturing Model

The initial model used for the estimates of equipment needed for the production facility was developed with an earlier version of Extend. When later versions of Extend were released, the existence of custom modules in the model limited its flexibility. Changes in the coding structure introduced in the updated versions were important to allow the code to run more efficiently, but the custom modules were important as well. Ultimately, a completely converted model was developed based exclusively on modules that could be used in Extend Version 5.

While there is some mass split data included in the model to account for recycle and waste streams, the initial Extend model was never used to perform a detailed mass balance calculation. Rather than proceed with validating the mass balance calculations, the modeling effort switched to reworking the model with a database interface as discussed next.

3.2 Transport System Model

Development of a transport system model began shortly after the conversion of the Extend model to Version 5 was completed. The initial effort used conventional Extend blocks and a hierarchical structure to represent the processes of calling a transport carrier, moving it to pick up material at the calling workstation, and then delivering the material to a destination workstation. A prototype model demonstrated that such a model could be created, but it also demonstrated that including that much logic into an Extend model of the entire facility would result in an extremely slow running model. Because of that observation, we consulted with Simulation Dynamics, Inc. discussing transport system modeling. After one day of discussing our modeling needs, a database approach was recommended that would give us far more flexibility and far faster running times than could be achieved with Extend alone.

The fundamental characteristic of the database approach is that all model input and output information is contained in tables that can be accessed through the database interface. This ability to centralize all model data in a single location allowed development of a system model with, basically, two generic building blocks, a workstation and a transporter. A portion of the transport system model is shown in Figure 1. This figure is a partial snapshot of the model that includes enough detail to show the essential features.

The model is constructed from two fundamental material handling modules, a workstation and a transporter. Each of the gray boxes in Figure 1 is a Workstation, and each of the “wagon-like” icons represents a transporter. Each workstation has a unique name based on its location in the plant. This allows the transport system to identify the location of the workstation and determine on which transport line it lies. Each transporter also has a unique identifier by which it determines those workstations it services. Each workstation and transporter icon includes a color changing “status” indicator box. This status box is green, if the workstation or transporter is “Idle” and available, red if “Busy” in operation, and blue if “Down – Waiting for Item Transport”. The transporters can also show as purple, indicating “Busy – Moving Empty”.

4. Model Overview

The operation of the model centers on the workstations and the transporters. The workstations process material, while the transporters move material from one location to another. All material entering the system is uniquely identified with an Item ID, by which it can be tracked through the entire system. All processes and movements of material are linked to this Item ID. Once an Item ID is assigned, it is never removed from the database. If an item is consumed as part of the manufacturing process, or if it fails a particular processing step and becomes waste or scrap, its nature can change, but the Item ID is not removed from the database. The Item ID is simply closed out and left in the database for information tracking purposes.

Material processing begins with the generation of a mass of source material introduced at the input Hood in the model. This source material is assigned an Item ID based on the next available record in the database, and it is assigned a material type based on input logic specified by the user. The material type allows the transport system to enter a *Process* table to determine what is the next process function to be performed on the item. The Transporter then searches the *Workstations* table to determine whether any workstations that perform that process are currently available. If so, and if the transport path to that workstation is available, the item is authorized to move. The Transporter moves from its current location to the Items location and the item is moved to the target workstation. This description of the transport system logic is applicable for essentially every material move that the system has to make.

When an item is delivered to a workstation, the input processing logic in the workstation reads the Item ID to find the item's record in the *Items* table. From this record, the workstation can determine the item type, the process step number, and the mass of any materials being tracked for this item. From the item type, the workstation identifies the *Process* table, which specifies the time needed to complete this process step and the distribution of mass components as a result of performing the process. The elapsed time is entered into the Activity Delay block representing the time delay for this process step in the Extend model. The Extend model allows the time delay to pass, after which the masses are distributed into bins tracked in the *Workstations* table, and the mass of the item is updated as appropriate. All of the input data required for this calculation is contained in the *Process* table. The workstation then issues a request to its local transport system for the material to be removed. The item is not removed from the workstation until the transport system returns an authorization to move the item.

Material movement for all the transporters uses the same logic. When a workstation issues a request for material transport (which carries the Item ID), the request is received at the transporter input Catch block. Since each workstation knows the identifier of its local transporter, the transporter receiving the request for transport already knows that the request is legitimate. It reads the Item ID from the request, determines its current status, and assigns a transport priority. The item request is then entered into the transporter input queue by order of decreasing priority. Each transporter maintains its own input queue as a separate table in the database. This queue stores all pending requests to the transporter, but in addition, provides a measure of the maximum backlog each transporter experienced during the course of a particular run.

Once an item is entered into the transporter queue, when the transporter becomes idle, it queries the queue and locates the highest priority item waiting to be moved. With the Item ID, the transporter identifies the appropriate *Process* table, determines the next process step and if a workstation performing that function is available. If the destination workstation is on the same transport line, the item is moved. If, on the other hand, the destination workstation is on a different transport line, the local transporter checks to see if the drop box on its line is available. If so, the item is moved to the

local drop box. If not, the transporter skips the item and looks for the next highest priority item in the queue. Once an item is approved for transport, its entry in the queue is deleted. A transport authorization is sent back to the requesting workstation and the workstation releases the item to the transport system. At this time, the workstation updates its mass inventory records to account for the item leaving. If the item was the last one in the workstation awaiting transport, the workstation status is set to "Idle" and the workstation becomes available for processing another item.

4.1 Model Properties

4.1.1 Mass Balance and Inventory

A mass balance and plant mass inventory calculation is perhaps one of the key capabilities of a production model. The production model described here was designed to take maximum advantage of the database interface to track any number of materials through the production process efficiently. The mass balance calculations are associated with the Workstation calculations, since the workstations account for nearly all of the mass in the plant and all of the accumulation of material that is no longer associated with a production, or product, item.

Material is introduced into the production process as feed material. The model introduces the feed with some characteristic mass that is assigned to the feed item. This mass is entered into the database when the feed item is first generated, and it remains associated with that feed item until a process performed in a workstation distributes the mass to other items or storage locations. When the feed item is converted into a process item, say a particular part type, a new item is created with the mass characteristic of that part type. Any remaining Material remains in a storage location for use with subsequent parts. The new part item is then transported in accordance with its *Process* table.

Mass tracking in each workstation is based on several categories of material associated with the manufacturing process. These include product material associated with the part being produced, recycle metal, residue, and waste. The model associates a specified amount of material with rags and tools used in part manufacturing. These are stored in the workstations until a specified quantity accumulates, and are then assigned an item number and transported for output processing according to their own *Process* table. The importance of associating the movement of all materials to and from the workstations with an item number is to ensure that the load on the transport system is properly represented not only for product transport, but also for all processes required to maintain the workstations in an operating condition.

Ultimately, all material is transported to an exit location. Mass balance calculations are performed on the plant inlet and outlet, or exit, locations to give an integral evaluation of a plant material balance. These are compared to balances on the individual workstations to ensure agreement, thereby providing an automatic, independent validation of the mass balance calculation.

4.1.2 Transport Time

The time required to transport an item from one location to another is calculated for each transfer after the transporter and workstations have been determined to be available. There are two tables in the database used to calculate the time. One is a *Distance* table that gives the distance from each location in the plant to its nearest neighbors, whether they be workstations or transport system transfer points. The second table is a *Paths* table from which the path from any point in the facility to any other point in the facility can be calculated.

By using the *Paths* table, the transport system logic can calculate the route between any two points by knowing the starting and ending point. When transport of an item is approved, three locations are read from the database: current location of the transporter, location of the sending workstation, and location of the receiving workstation. If the receiving workstation is not on the same local transport line as the sending workstation, the local dropbox becomes the intermediate destination. The dropbox is the transfer point between the local transport and the so-called Cross-Town-Trolley (CTT), which runs the length of the facility. By recording the ultimate destination in the database and using the dropbox as an intermediate point, the logic for the CTT can be identical to that for the local transporters, thereby simplifying the model logic.

Once the three locations are identified, the distances between them can be found from the *Distances* table. The transport time is then calculated as the total distance that must be traversed by the transporter moving empty from its current location to the sending workstation, and then from the sending workstation to the destination, divided by the speed of the transporter. Any additional times such as transfer times from a workstation to the transporter, or a hand-off time from one section of the transport system to another are added to the distance dependent term to give a total elapsed time for the transfer of material. The *Transporter* table records the total amount of time the transporter was moving while empty, total time moving full, and total idle time. Separate records are kept for each transporter system for later evaluation of the transport systems.

4.1.3 Transport priority

The calculation of transport priority for any given item is a complex process that has the capability of disrupting material movement in the plant. As a general rule of thumb, the current model assigns higher priority to items that are “downstream”; i.e., items that are further along in the manufacturing process will typically be moved before items that have not progressed as far. The reason for this logic is that the downstream portions of the manufacturing line have to be kept clear to prevent a bottleneck from developing. Because there is recycle involved in the production process, downstream items occasionally have to move back to a process upstream. These recycle requests must be processed with a high priority, or the workstation required for the rework might be occupied with an item that it won't be able to discharge because of a plugged process line.

While this general rule of thumb works acceptably well most of the time, some modifications are required to avoid upstream bottlenecks. Preliminary calculations have shown that from time to time, an item can get “stuck” in a workstation and never processed out because it has too low a priority. The item is effectively lost in a workstation and, in effect, removes that workstation from the plant. To prevent this condition from persisting, the transport system increments the priority on every item in its queue each time the queue is scanned for items awaiting transport. The size of the increment is still being investigated, but this process ensures that over time, even items that start with a low transport priority will eventually work their way through the system. Since the priority is recalculated every time an item enters the transport queue, once an originally low priority item is moved to the next process step, its priority is higher when it reenters the queue, since it is now further along in the manufacturing process.

There is a specialized version of the workstation that is also used to prevent items “sticking” within production workstations. If an item has completed a processing step and has issued a transport request but the transporter can not find an available next workstation, rather than sticking within the current workstation, the item will be moved to a vault serving that area of the plant. Vaults receive items like regular workstations, log the item into its inventory, and immediately issue a transportation request. The number of items stored in the vault is unlimited and the vault queue length can be reviewed to determine the maximum number of items that were in the vault during that run.

4.1.4 Workstations

Each process location is identified as a workstation, consistent with the plant layout diagram used to determine manufacturing space needed to accomplish the production goals. The principal workstation identifier is related to its physical location in the plant. The *Workstations* table, as shown in Figure 2, lists each of these locations as a separate record, each of which contains the characteristics for that particular workstation. The layout shown in Figure 1 shows the Foundry section of the model. It is designed after the proposed plant layout, although the physical arrangement shown in the figure does not impact the functioning of the model. The information in each workstation record includes: the type of process performed in the workstation, the instantaneous status of the workstation, the type of item currently being processed, if any, the number of items received by that workstation, and several columns of material data cataloging work materials and mass inventories. There are also columns for recording transport information needed by the transport system to identify locations for receiving and delivering materials (Catch block ID numbers). These additional columns are not shown in Figure 2. While only a small number of specific materials are currently tracked for mass inventory calculations, additional materials or chemical species can be added by simply adding a column to the *Workstations* table and adding an equation to the workstation module to represent the disposition of the new species. There is no limit to the number of species that can be added.

4.1.5 Items

Every piece of material moved in the plant is identified as an item and is recorded in the *Items* table. Items data includes the Item ID, the item type, such as a part type, recycle, rags, etc., its mass, its current processing step number, and its current location. The Item ID is used as the identifier by which the transport system recognizes the item and determines its appropriate disposition. It is through the use of this Item ID that the need to carry "attributes" in the Extend model is minimized. In fact, only the Item ID and two (2) Catch block numbers are included as attributes on items in the Extend model environment. An example of the *Items* table is shown in Figure 3.

The *Items* table also includes process evaluation data. In particular, the total process time is recorded to track the total amount of time spent working on a particular part. The total transport time is recorded to show how much time the part spent in transit. The path it took, namely, all of the workstations in which it was located, is recorded to help identify bottlenecks.

Workstations															
string	string	string	string	integer	real	real	real	real	real	real	real	real	real	real	real
Workstation ID	Workstation Type	Workstation Status	Item Type	Items Received	Good Rags	Spent Rags	Good Tooling	Spent Tooling	Product Material	Recycle Material	Waste Material	Residue Material	Removed Pu		
Hood	Feed	Down-Waiting	Feed	0	50	0	50	0	0	0	0	0	0	0	0
Exit	Exit	Idle	Feed	0	50	0	50	0	0	0	0	0	0	0	0
Foundry 1-01	Unpack	Idle	Feed	0	100	0	100	0	0	0	0	0	0	0	0
Foundry 1-02	FND-3	Idle	Feed	0	100	0	100	0	0	0	0	0	0	0	0
Foundry 1-03	FND-3	Idle	Feed	0	100	0	100	0	0	0	0	0	0	0	0
Foundry 1-04	FND-3	Idle	Feed	0	100	0	100	0	0	0	0	0	0	0	0
Foundry 1-05	FND-5	Idle	Feed	0	100	0	100	0	0	0	0	0	0	0	0
Foundry 1-06	FND-5	Idle	Feed	0	100	0	100	0	0	0	0	0	0	0	0
Foundry 1-07	FND-6	Idle	Feed	0	100	0	100	0	0	0	0	0	0	0	0
Foundry 1-08	FND-5	Idle	Feed	0	100	0	100	0	0	0	0	0	0	0	0
Foundry 1-09	FND-7A	Idle	Feed	0	100	0	100	0	0	0	0	0	0	0	0
Foundry 1-10	FND-7A	Idle	Feed	0	100	0	100	0	0	0	0	0	0	0	0
Foundry 1-11	FND-7A	Idle	Feed	0	100	0	100	0	0	0	0	0	0	0	0
Foundry 1-12	FND-7A	Idle	Feed	0	100	0	100	0	0	0	0	0	0	0	0
Foundry 1-13	FND-7A	Idle	Feed	0	100	0	100	0	0	0	0	0	0	0	0
Foundry 1-14	FND-7A	Idle	Feed	0	100	0	100	0	0	0	0	0	0	0	0
Foundry 1-15	Inspection Process	Idle	Feed	0	100	0	100	0	0	0	0	0	0	0	0
Foundry 1-16	FND-7B	Idle	Feed	0	100	0	100	0	0	0	0	0	0	0	0
Foundry 1-17	FND-8	Idle	Feed	0	100	0	100	0	0	0	0	0	0	0	0
Foundry 1-18	FND-7B	Idle	Feed	0	100	0	100	0	0	0	0	0	0	0	0
Foundry 1-19	FND-9	Idle	Feed	0	100	0	100	0	0	0	0	0	0	0	0
Foundry 2-01	FND-3	Idle	Feed	0	100	0	100	0	0	0	0	0	0	0	0
Foundry 2-02	FND-3	Idle	Feed	0	100	0	100	0	0	0	0	0	0	0	0
Foundry 2-03	FND-3	Idle	Feed	0	100	0	100	0	0	0	0	0	0	0	0
Foundry 2-04	FND-3	Idle	Feed	0	100	0	100	0	0	0	0	0	0	0	0
Foundry 2-05	FND-5	Idle	Feed	0	100	0	100	0	0	0	0	0	0	0	0
Foundry 2-06	FND-5	Idle	Feed	0	100	0	100	0	0	0	0	0	0	0	0
Foundry 2-07	FND-6	Idle	Feed	0	100	0	100	0	0	0	0	0	0	0	0
Foundry 2-08	FND-5	Idle	Feed	0	100	0	100	0	0	0	0	0	0	0	0
Foundry 2-09	FND-7A	Idle	Feed	0	100	0	100	0	0	0	0	0	0	0	0
Foundry 2-10	FND-7A	Idle	Feed	0	100	0	100	0	0	0	0	0	0	0	0
Foundry 2-11	FND-7A	Idle	Feed	0	100	0	100	0	0	0	0	0	0	0	0
Foundry 2-12	FND-7A	Idle	Feed	0	100	0	100	0	0	0	0	0	0	0	0
Foundry 2-13	FND-7A	Idle	Feed	0	100	0	100	0	0	0	0	0	0	0	0
Foundry 2-14	FND-7A	Idle	Feed	0	100	0	100	0	0	0	0	0	0	0	0
Foundry 2-15	FND-8	Idle	Feed	0	100	0	100	0	0	0	0	0	0	0	0
Foundry 2-16	FND-7B	Idle	Feed	0	100	0	100	0	0	0	0	0	0	0	0
Foundry 2-17	FND-8	Idle	Feed	0	100	0	100	0	0	0	0	0	0	0	0
Foundry 2-18	FND-7B	Idle	Feed	0	100	0	100	0	0	0	0	0	0	0	0
DropBox 1	Drop Box	Down-Waiting	Feed	0	100	0	100	0	0	0	0	0	0	0	0
DropBox 2	Drop Box	Idle	Feed	0	100	0	100	0	0	0	0	0	0	0	0
DropBox 3	Drop Box	Idle	Feed	0	0	0	0	0	0	0	0	0	0	0	0
DropBox 4	Drop Box	Idle	Feed	0	0	0	0	0	0	0	0	0	0	0	0
DropBox 5	Drop Box	Idle	Feed	0	100	0	100	0	0	0	0	0	0	0	0

Figure 2. Workstations Table

4.1.6 Process

Items processed in the plant, whether product items being produced according to a specified production schedule, or miscellaneous items such as workstation supplies, recycle material, etc., are processed according to a sequence of operations specified in a *Process* table. The *Process* table is perhaps the focal point for all of the transport system logic, since it is used to identify the next functional step to be performed for any item requesting transport. Every unique item type has an associated *Process* table that lays out all of the steps required to perform that process. This includes a separate *Process* table for each part type to be produced, a table for each specific waste or recycle stream to be processed, and tables for supply streams needed to keep workstations stocked with materials such as tools and rags. In addition, a *Process* may end at a workstation, which transforms the item into another item type, which follows a different *Process* table (i.e. raw material that gets processed into a part, or parts that get combined into an assembly).

Items													
Table	integer	string	string	string	string	integer	string	real	integer	real	real	integer	integer
Notes	Item ID	Item Type	Item Status	Current Location	Destination	Step Number	Operation	Item Mass	Pass Number	Process Time	Transport Time	Transport Priority	Became Item
Fields													
1	1	Feed	Failed	Foundry 1-15		8	FND-7B	0	1	3153.815948	193.7	0	19
2	2	Feed	Failed	Foundry 1-15		8	FND-7B	0	1	3211.704204	224.3	0	21
3	3	Feed	Failed	Foundry 1-15		8	FND-7B	0	1	3211.752136	224.5	0	23
4	4	Feed	Failed	Foundry 1-15		8	FND-7B	0	1	3213.833372	224.1	0	27
5	5	Feed	Failed	Foundry 1-15		8	FND-7B	0	1	3212.244402	224.3	0	29
6	6	Feed	Failed	Foundry 1-15		8	FND-7B	0	1	3209.701378	224.1	0	31
7	7	Feed	Finished	Exit		11	Exit	1.511513181	1	3358.535252	244.9	0	0
8	8	Feed	Finished	Exit		11	Exit	1.499648856	1	3360.103128	254.9	0	0
9	9	Feed	Failed	Foundry 1-15		8	FND-7B	0	1	3149.660202	132.1	0	120
10	10	Feed	Failed	Foundry 1-15		8	FND-7B	0	1	3152.469683	152.1	0	404
11	11	Feed	Failed	Foundry 1-15		8	FND-7B	0	1	3210.954142	214.1	0	247
12	12	Feed	Failed	Foundry 1-15		8	FND-7B	0	1	3212.650035	234.3	0	249
13	13	Feed	Failed	Foundry 1-15		8	FND-7B	0	1	3209.117563	233.7	0	181
14	14	Feed	Failed	Foundry 1-15		8	FND-7B	0	1	3210.674123	234.3	0	33
15	15	Feed	Finished	Exit		11	Exit	1.510889207	1	3421.044168	337.1	0	0
16	16	Feed	Failed	Foundry 1-15		8	FND-7B	0	1	3209.657061	234.3	0	36
17	17	Feed	Finished	Exit		11	Exit	1.510790193	1	3420.234906	337.1	0	0
18	18	Feed	Finished	Exit		11	Exit	1.533622608	1	3420.000144	337.1	0	0
19	19	Recycle	Finished	Exit		1	Exit	1.689559634	1	30.11869902	51.6	0	0
20	20	Feed	Failed	Foundry 1-15		8	FND-7B	0	1	3210.595518	234.1	0	40
21	21	Recycle	Finished	Exit		1	Exit	1.670119926	1	30.67828218	51.6	0	0
22	22	Feed	Finished	Exit		11	Exit	1.483589873	1	3424.422966	337.1	0	0
23	23	Recycle	Finished	Exit		1	Exit	1.68674266	1	29.80785913	51.6	0	0
24	24	Feed	Finished	Exit		11	Exit	1.508582146	1	3419.298133	337.3	0	0
25	25	Feed	Finished	Exit		11	Exit	1.524995179	1	3417.3755	336.9	0	0
26	26	Feed	Failed	Foundry 1-15		8	FND-7B	0	1	3215.314495	234.1	0	45
27	27	Recycle	Finished	Exit		1	Exit	1.692534889	1	28.91079648	51.6	0	0
28	28	Feed	Finished	Exit		11	Exit	1.513450534	1	3422.201832	337.3	0	0
29	29	Recycle	Finished	Exit		1	Exit	1.67544154	1	30.34211627	51.6	0	0
30	30	Feed	Failed	Foundry 1-15		8	FND-7B	0	1	3210.004679	234.3	0	48
31	31	Recycle	Finished	Exit		1	Exit	1.6778845	1	29.12989054	51.6	0	0
32	32	Feed	Finished	Exit		11	Exit	1.532503453	1	3421.684291	336.9	0	0
33	33	Recycle	Finished	Exit		1	Exit	1.660643175	1	29.59961558	51.6	0	0
34	34	Feed	Failed	Foundry 1-15		8	FND-7B	0	1	3215.607768	234.5	0	51

Figure 3. Items table

5. Preliminary Results

Model calculations to date have focused on debugging, verifying, and validating the models for application to part production issues. As such, the results produced so far demonstrate the capabilities of the models, that when realistic data are entered into the models, the results will give an accurate reflection of plant behavior.

5.1 Manufacturing model results

The manufacturing model has been designed to provide three key pieces of information, two of which are immediate, and the third longer term:

1. A throughput analysis upon which an equipment list will be based,
2. A mass balance to evaluate input requirements and feed purification capacity requirements, and
3. An evaluation of transport system design parameters to ensure adequate material handling capability.

Of these three requirements, the initial manufacturing model discussed earlier satisfied the first. The second objective, a mass balance, is an integral part of the current task to select a feed production process. In particular, the recycle rate of supply material from the manufacturing plant back to purification will have a direct impact on the capacity required to support production. Some sample results are presented in Table 5 and discussed in the next few paragraphs. The third objective, an analysis of the transport system, is an integral part of the manufacturing model discussed here, and some sample results are presented in Table 6. A brief discussion of the transport system modeling will follow the mass balance discussion, but a detailed transport system analysis is not an immediate need.

It is important to note that *none of the data used as input to the manufacturing model are related to actual production parameters* at this time. The purpose of discussing output results is to show the capabilities that have been included in the model and how they can be used to evaluate plant performance. The numbers themselves are simply for testing purposes to ensure that the model is working correctly, that mass is being conserved, and that the distribution of mass resulting from the production processes is being handled properly. While the mass splits are not an input parameter per se, they are an important characteristic of the manufacturing process and will be used to ensure agreement with plant design assumptions.

Table 5 is a snapshot of a portion of the mass balance summary table filled in by the manufacturing model as it runs. A key included with the table provides a brief description of each of the columns. Every item that moves through the facility is assigned a unique Item ID. This Item ID is used to track the progress of the item through the plant. When recycle or waste materials accumulate in the workstations to the point that they must be removed, they are assigned a unique Item ID and transported out. The mass of each of these items is tracked in the *Items* table. Whenever an item enters (or leaves) the facility, its mass is added to the appropriate mass summary table along with the time of the material movement. The accumulation of this mass movement data provides a time dependent mass balance as shown in Table 5. The tools available in Microsoft Excel™ can be used for any post-processing analysis desired.

The mass balance calculated in the final model includes the same parameters that are used in the baseline model. These materials include such waste streams as material lost on rags and tools in the workstations, and recycle streams associated with excess material in casting and machining

operations. The disposition of these material streams has been evaluated and agreed upon through the course of several Facility Working Group (FWG) meetings and associated special meetings with subject matter experts. Ultimately, the mass balance calculation will provide:

1. The production rate of the facility as a function of the number of workstations, or the equipment list.
2. The mass inventory of the plant required to support production, including the time dependent rate at which the plant “fills up” when production first starts.
3. The overall production capacity required as a function of recycle, part and equipment failures, inspection and approval rates, etc.
4. The impact of the transport system on material flow in the plant.

The transport system model, which is an integral part of the mass balance model, tracks all movements of the transport system. It assumes that each group of workstations has a dedicated transporter as shown in Figure 1. The local transporters are connected to a so-called “cross-town” system that moves material between the local systems. The model is designed to allow any operation to be assigned to any workstation through a designation in the *Workstations* table. Each Item in process has a unique Process identifier associated with it. At the end of any given process, the transport system can access the *Process* table, identify the next process to be performed for that item, find a workstation designated to perform that process, and move the item to that workstation. This all happens automatically while ensuring that workstations, transporters, and transport paths are available, so no conflicts are encountered while moving material in the plant. The ability to assign a unique process to each item, and to include a unique *Process* table for each process, allows the model to evaluate production of different part types simultaneously. Table 6 shows some sample results for the Transporter. It includes each transporter ID, the time that transporter was moving empty (to go pick up material), the time it moved full, and location information identifying the current location of the transporter and its next destination. This output will provide an overall assessment of the transport system capacity.

Item ID	Item Type	Item Mass	Time	Direction	Time(days)	MassIn	MassOut	Product	Recycle	Tooling Out	Rags Out	Waste	In-Out
1041	Tooling Out	0.2	171462.6	Out	119.07	623.89	376.21	24.89	202.31	23.30	97.60	14.06	247.68
1055	Feed	2.017369	171630	In	119.19	625.91	376.21	24.89	202.31	23.30	97.60	14.06	249.70
1053	Rags Out	0.2	171683.4	Out	119.22	625.91	376.41	24.89	202.31	23.30	97.80	14.06	249.50
1054	Rags Out	0.2	171833.9	Out	119.33	625.91	376.61	24.89	202.31	23.30	98.00	14.06	249.30
1056	Rags Out	0.2	172190.7	Out	119.58	625.91	376.81	24.89	202.31	23.30	98.20	14.06	249.10
1045	Rags Out	0.2	172309.7	Out	119.66	625.91	377.01	24.89	202.31	23.30	98.40	14.06	248.90
1057	Rags Out	0.2	172494.3	Out	119.79	625.91	377.21	24.89	202.31	23.30	98.60	14.06	248.70
1058	Rags Out	0.2	172622.3	Out	119.88	625.91	377.41	24.89	202.31	23.30	98.80	14.06	248.50
1063	Feed	2.011722	172730	In	119.95	627.92	377.41	24.89	202.31	23.30	98.80	14.06	250.51
1059	Rags Out	0.2	172777.1	Out	119.98	627.92	377.61	24.89	202.31	23.30	99.00	14.06	250.31
1061	Rags Out	0.2	172953.5	Out	120.11	627.92	377.81	24.89	202.31	23.30	99.20	14.06	250.11
1060	Rags Out	0.2	173120.7	Out	120.22	627.92	378.01	24.89	202.31	23.30	99.40	14.06	249.91
1068	Feed	1.961328	173250	In	120.31	629.88	378.01	24.89	202.31	23.30	99.40	14.06	251.87
1046	Tooling Out	0.2	173292.1	Out	120.34	629.88	378.21	24.89	202.31	23.50	99.40	14.06	251.67
1066	Rags Out	0.2	173487.5	Out	120.48	629.88	378.41	24.89	202.31	23.50	99.60	14.06	251.47
1070	Rags Out	0.2	173603.8	Out	120.56	629.88	378.61	24.89	202.31	23.50	99.80	14.06	251.27
1064	Rags Out	0.2	173717.5	Out	120.64	629.88	378.81	24.89	202.31	23.50	100.00	14.06	251.07
1072	Feed	1.973959	173830	In	120.72	631.86	378.81	24.89	202.31	23.50	100.00	14.06	253.05
1065	Rags Out	0.2	173834.8	Out	120.72	631.86	379.01	24.89	202.31	23.50	100.20	14.06	252.85
1069	Tooling Out	0.21	173971.2	Out	120.81	631.86	379.22	24.89	202.31	23.71	100.20	14.06	252.64
1062	Tooling Out	0.2	174087.8	Out	120.89	631.86	379.42	24.89	202.31	23.91	100.20	14.06	252.44
1074	Feed	1.956791	174150	In	120.94	633.81	379.42	24.89	202.31	23.91	100.20	14.06	254.39
1047	Rags Out	0.2	174204.7	Out	120.98	633.81	379.62	24.89	202.31	23.91	100.40	14.06	254.19
1071	Rags Out	0.2	174375	Out	121.09	633.81	379.82	24.89	202.31	23.91	100.60	14.06	253.99
1067	Recycle	1.682641	174491.6	Out	121.17	633.81	381.50	24.89	204.00	23.91	100.60	14.06	252.31
1077	Feed	2.02959	174565	In	121.23	635.84	381.50	24.89	204.00	23.91	100.60	14.06	254.34
1021	Rags Out	0.2	174661.6	Out	121.29	635.84	381.70	24.89	204.00	23.91	100.80	14.06	254.14
1051	Rags Out	0.2	174800.3	Out	121.39	635.84	381.90	24.89	204.00	23.91	101.00	14.06	253.94
1081	Feed	2.018566	174820	In	121.40	637.86	381.90	24.89	204.00	23.91	101.00	14.06	255.96
1076	Rags Out	0.2	174927.4	Out	121.48	637.86	382.10	24.89	204.00	23.91	101.20	14.06	255.76
1073	Rags Out	0.2	175050.4	Out	121.56	637.86	382.30	24.89	204.00	23.91	101.40	14.06	255.56
1075	Rags Out	0.2	175168.9	Out	121.65	637.86	382.50	24.89	204.00	23.91	101.60	14.06	255.36
826	Feed	0.157305	175305.1	Out	121.74	637.86	382.66	25.05	204.00	23.91	101.60	14.06	255.20
1078	Waste	2.003031	175423.9	Out	121.82	637.86	384.66	25.05	204.00	23.91	101.60	16.06	253.20
1082	Rags Out	0.2	175547.4	Out	121.91	637.86	384.86	25.05	204.00	23.91	101.80	16.06	253.00
1086	Feed	2.010517	175555	In	121.91	639.87	384.86	25.05	204.00	23.91	101.80	16.06	255.01
816	Feed	0.152606	175800.5	Out	122.08	639.87	385.02	25.20	204.00	23.91	101.80	16.06	254.86
1083	Recycle	1.691928	175920.7	Out	122.17	639.87	386.71	25.20	205.69	23.91	101.80	16.06	253.16
1090	Feed	2.004376	175940	In	122.18	641.88	386.71	25.20	205.69	23.91	101.80	16.06	255.17
1084	Rags Out	0.2	176074.7	Out	122.27	641.88	386.91	25.20	205.69	23.91	102.00	16.06	254.97
1085	Tooling Out	0.2	176203.7	Out	122.36	641.88	387.11	25.20	205.69	24.11	102.00	16.06	254.77
852	Feed	0.154954	176317.9	Out	122.44	641.88	387.26	25.35	205.69	24.11	102.00	16.06	254.61

Key:

- Item ID Unique identifier for each item transported
- Item Type Specific item type, part type, waste stream identifier, etc.
- Item Mass Item mass in consistent units, typically kilograms
- Time Time of the recorded transaction in minutes
- Direction Flag for mass transfer In or Out of facility
- Time(days) Transaction time converted to days
- MassIn Cumulative mass into facility
- MassOut Cumulative mass out of facility
- Product Cumulative mass leaving facility as product (parts)
- Recycle Cumulative mass leaving facility as recycle (this may be converted to an internal recycle stream)
- Tooling Out Cumulative mass leaving the facility on tooling
- Rags Out Cumulative mass leaving the facility on rags
- Waste Cumulative mass leaving the facility as waste
- In – Out Net cumulative mass still within the facility

Table 5. Sample manufacturing model output

Transporter							
Note for Field 1	Note for Field 2	Note for Field 3	Note for Field 4	Note for Field 5	Note for Field 6	Note for Field 7	Note for Field 8
string	string	real	real	string	real	string	string
Transporter ID	Trans Destination	Trans Empty Time	Trans Full Time	Trans Current Location	Trans Idle Time	Trans Status	Next Workstation ID
Foundry 1	Foundry 1-16	82782.3	79029.4	FOUNDRY 1-1	0	Idle	Foundry 1-16
Foundry 2	Foundry 2-03	46977.7	46606	FOUNDRY 2-0	0	Busy	Foundry 2-03
Mach 1	DropBox 3	15786.7	14543.7	DropBox 3	0	Idle	DropBox 3
Mach 2	Mach 2-13	104002	102237	Mach 2-13	0	Idle	Mach 2-13
WA 1	Assmby 1-02	55045.8	55731.3	Assmby 1-02	0	Idle	Assmby 1-02
PA&I 1	PA&I 1-30	135949.09	135870.6	PA&I 1-30	0	Busy	PA&I 1-30
FND Feed	DropBox 7	11497.2	11497.2	DropBox 7	0	Idle	DropBox 7
FND Exit		0	0	DropBox 8	0	Idle	
MAWS Vault 1		0	0	DropBox 9	0	Idle	
APS Vault 1	Exit	36340.7	36340.8	Exit	0	Idle	Exit
CTT	DropBox 6	111810.1	107497.1	DropBox 6	0	Busy	DropBox 6
WA 2	DropBox 11	27451.5	28050.9	DropBox 11	0	Busy	DropBox 11

Table 6. Sample transport system output from the manufacturing model.