Simulation as an Intuition Building Tool For Factory Physics

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Abstract

In today's manufacturing environment it is absolutely critical to be competitive in order to guarantee a company's sustainability. One way to achieve this sustainability is to count on management's ability to effectively make decisions dealing with its manufacturing resources. To do this management must rely on a systematic description of the manufacturing system and a set of performance measures used to evaluate and control the system. One way to do this is to employ the concepts and laws of Factory Physics. These concepts and laws can become very powerful tools to identify and understand a system's weak points, permitting management to design ways to turn them into leverage points. But to do this management needs to have good intuition and this can only be done if it fully understands the meaning of these concepts and laws. In order to facilitate the understanding of Factory Physics a computer based simulation model was developed as part of a learning tool to be used in conjunction with a formal Factory Physics course. This paper examines the model and its usefulness as a learning tool.

1. INTRODUCTION

It has been said that we are moving towards a service oriented economy. Yet everyday more and more products are developed and these have shorter life cycles than products did a decade or two ago. If this is true, then where and by whom will the products we consume everyday be manufactured and assembled? The bottom line is that manufacturing still remains an important element in any country's economy. The new global economy has forced changes in every manufacturing sector, but before discussing these changes lets define exactly what manufacturing is.

Manufacturing involves the processing of less valuable materials into a more valuable form. It usually requires a complex set of organized steps involving physical components to transform these materials. A manufacturing system is always trying to fulfill the following goals: innovation of products, processes and organization, striving for increased quality and more added value, to reduce the time to market of their products, to reduce both its manufacturing and customer lead times and finally to guarantee cost competitive products. Unfortunately these types of systems are very unforgiving of errors.

The above cited goals have been around since the beginning of the industrial revolution. However, the competitive context has changed and now includes the following characteristics: not only a global market but a global supply base, as well as an important emphasis on continuous improvement and innovation, a kin interest on environmental issues including environmental impacts of products and processes, and the organization's social responsibility.

As stated by Williams and Johnson (2004) the "bottom line" for manufacturing businesses is short-term performance with future business growth, more variety and shorter product life cycles, more competition and regulation, more precision and complexity, and more data to be turned into knowledge, [1].

In order to meet these new competitive challenges management needs to fully understand its manufacturing system; only this way will it be able to model the system and improve its decision making processes. One such way to systematically describe, model and improve a manufacturing system was developed by Spearman and Hopp, and is known as Factory Physics. This approach relies on: (1) a set of basic concepts, involving variability, reliability and queuing theory, (2) intuition and (3) synthesis.

As will be discussed in this paper the first and last components can be understood and put into practice separately by simply studying the corresponding theory. However the second component, intuition, can only be put into practice when the other two components are understood jointly under a true systemic thinking approach and once the individual has had a chance to experiment with different operating scenarios of the same manufacturing system.

It is precisely here where the strengths of computer based simulation will be used to permit the individual to "see and evaluate" how the different operating scenarios will impact the manufacturing system's performance. In other words, through the use of a computer based simulation model the individual will have the chance to "play" with a virtual manufacturing system and *learn* from his actions, developing the sought after intuition.

2. FACTORY PHYSICS

Factory physics as a method seeks to develop a science of manufacturing based on basic concepts as a starting point from which fundamental principals are derived forming what is known as "manufacturing laws" and identifying general applications from other manufacturing philosophies. Factory physics is not another buzzword; it was developed based on the scientific method and has the following common features with the study of physics: (1) it uses a problem-solving framework, (2) relies on a technical approach and (3) considers the role of intuition about a system's behavior important in order to make good and timely decisions related to actions affecting the system.

Factory physics considers the following three components as critical skills for the manager of the future:

2.1. The Basics

According to Hopp and Spearman (2000) the language and elementary concepts for describing manufacturing systems are essential prerequisites for any manufacturing manager, [2]. These concepts include variability, reliability and the behavior of queuing systems. The following are some examples of the basics used in factory physics:

2.1.1. Little's Law

This is the first law for factory physics, Little's Law (Little 1961) is expressed as:

$$WIP = TH \times CT$$

Simply put, work-in-process (WIP) is equal to throughput (TH) multiplied by cycle time (CT). For factory physics this relation holds true in the long term. Throughput is defined as the average output of a production process per unit time (parts per hour). Cycle time for a given process is the average time it takes to travel from the release of a job at the beginning of the process until it reaches a given stock point at the end of the process.

2.1.2. Coefficient of Variation (CV)

Factory physics uses the coefficient of variation (CV) as a relative measure of variability associated to a random variable. For factory physics this variability could refer to process time variability, flow variability or variability interactions represented as queuing systems. It can be determined by the following expression:

$$c = \frac{\sigma}{t}$$

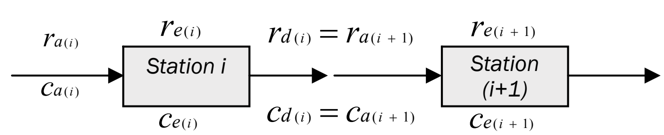
Since the main interest here is time, the expression uses *t* to denote the mean and *σ* the corresponding variance.

As will be seen later on, variability has a "corrupting" impact on system performance. For now the reader only needs to know that factory physics distinguishes between three variability classes, high variability having the most negative impact on a manufacturing system's performance.

Variability Class	CV
Low (LV)	c < 0.75
Moderate (MV)	0.75 ≤ c < 1.33
High (HV)	c ≥ 1.33

2.1.3. Queuing Theory

Factory physics employees queuing theory as a way to relate process time variability with flow variability resulting in the overall effects of variability on a production line. This will give us the means to evaluate the impact of variability on the key performance measures of any given manufacturing system, namely WIP, throughput and cycle time. The importance of this element to factory physics is that it easily introduces the concept of "propagation of variability" between a series of workstations; graphically this can be seen in the following figure:



Where $r_{a(i)}$, $r_{e(i)}$ and $r_{d(i)}$ respectively represent the arrival rate, the capacity and the departure rate for station *i*. At the same time $c_{a(i)}$, $c_{e(i)}$ and $c_{d(i)}$ respectively represent the arrival CV, CV of effective process time and the departure CV for the same station. The final result of this formulation is that depending on the class of variability present between workstations a queue will be formed. Resulting in new performances measures, namely CT_q the expected waiting time in queue and applying Little's Law WIP_q the expected WIP in queue. The former can be determined by the following expression:

$$CT_q(G/G/1) = \left(\frac{c_a^{\,2} + c_e^{\,2}}{2}\right)\left(\frac{u}{1-u}\right)t_e$$

This expression is known as the VUT equation and can be applied to systems characterized by general process and inter-arrival times.

2.2. Intuition

Before defining why intuition is important to factory physics lets define it in general terms. Intuition as defined by Webster's New World Dictionary, Third College Edition is:

1. The direct knowing or learning of something without the conscious use of reasoning; immediate apprehension or understanding.
2. The ability to perceive or know things without conscious reasoning.

Intuition is an immediate form of knowledge in which the knower is directly acquainted with the object of knowledge. Intuition differs from all forms of mediated knowledge, which generally involve conceptualizing the object of knowledge by means of rational/analytical thought processes, [3].

Hopp and Spearman (2000) define the importance of intuition as follows. The single most important skill of a manufacturing manager is intuition regarding the behavior of manufacturing systems. Solid intuition enables a manager to identify leverage points in a plant, evaluate the impacts of proposed changes, and coordinate improvement efforts, [2].

But exactly what are we referring to? Let's consider a basic expression from physics as an example:

$$F = ma$$

The above expression is said to be intuitive because just by looking at it we can arrive at conclusions such as; for a given mass, doubling the forces necessarily means that we had to have doubled the acceleration.

Factory physics heavily relies on the already mentioned basics to model and better understand the environment of a given manufacturing system, only by doing this will a manufacturing manager develop the same type of intuition as the one developed by a high school student from the above expression. When applied to manufacturing, this skill becomes critical in the decision making process.

To develop this intuition factory physics relies on a set of laws, the first of which was already stated, Little's Law. The following is a small sample of the laws which make up the fundamental principals of factory physics:

2.2.1. Law (Variability):

Increasing variability always degrades the performance of a production system.

2.2.2. Law (Variability Buffering):

Variability in a production system will be buffered by some combination of

- Inventory
- Capacity
- Time

2.2.3. Law (Move Batching):

Cycle times over a segment of a routing are roughly proportional to the transfer batch size used over that segment, provided there is no waiting for the conveyance device.

2.2.4. Law (self-Interest):

People, not organizations are self-optimizing.

2.2.5. Law (Responsibility):

Responsibility without commensurate authority is demoralizing and counterproductive.

In all, factory physics utilizes a total of 22 laws to define its fundamental principals.

2.3. Synthesis

To Hopp and Spearman (2000) synthesis is close behind intuition on the list of important skills for a manufacturing manager; it implies the ability to bring together the many components of a system into an effective whole. Part of this ability is related to the ability to understand any tradeoffs and focus on critical system parameters. At the same time the manager needs to have the ability to step back and view the system under study from a holistic perspective, [2]. This approach to problem solving is based on what is known as the systems approach and radically differs from some operations research techniques that primarily focus on finding local optimums.

Understanding the whole system a manufacturing manager will be able to consider improvements based on different approaches, while at the same time remain sensitive to the effects of these changes in one area or another. Part of this understanding involves the laws governing human nature.

2.4. Operations Management

Finally, we must remember that factory physics was developed as a first approximation to a science of manufacturing, giving the manufacturing manager a set of principals from which they can better understand, model and manage a manufacturing system.

Ultimately factory physics involves operations management and as such begins with the definition of the system's objective. As in any management activity the decision maker has at his disposal a set of controls that he can change in an attempt to achieve the system's objective and at the same time can evaluate the performance of the system under study in terms of a set of measures.

A good analogy to understand the relationship between objective, controls and measures is given by Hopp and Spearmen (2000). The objective of any airplane trip is to take a group of passengers safely and on time from point A to point B. To do this a pilot relies on a set of controls while at the same time constantly monitors how his actions on the controls affect the measures of the plane's performance. In this case the relationship between controls and measures is defined by the science of aeronautical engineering. The objective for a plant manager is to contribute to the firm's sustainability by efficiently transforming raw materials into finished goods that will be sold. Just like the pilot, the plant manager also has many controls and measures to consider. Understanding the possible relationships between controls and measures is the primary goal of factory physics.

Due to the fact that there can be an infinite combination of production environments and business strategies it is impossible to define a single set of performance measures for all manufacturing systems. However, based on a set of system parameters factory physics defines seven efficiencies that measure the performance of a single – product line. The values for these performance measures can range from 0 to 1, when they approximate to 1 this means near perfect performance while values close to 0 indicate worst possible performance. These are:

2.4.1. System Parameters:

The following is a list of the system parameters factory physics uses to determine the before mentioned performance measures:

- TH = average throughput given by output rate from the line (parts/day).
- D = average demand rate (parts/day).
- TH(*i*)= average throughput at station *i*, includes multiple visits by some parts duo to routing or rework considerations (parts/day).
- r*(*i*) = ideal rate of station *i* not including detractors (parts/day).
- RMI= average raw material inventory level (parts).
- WIP= average work in process level in line (parts).
- FGI= average finished goods inventory level (parts).
- T^*_0= raw process time not including detractors (days).
- CT= average cycle time from release to stock point, which is either finished goods or an interline buffer (days).

2.4.2. Throughput Efficiency (*E_{TH}*):

It is a measure of how adequately a manufacturing system can satisfy demand.

$$E_{TH} = \frac{\min\{TH, D\}}{D}$$

Any shortage (TH < D) will degrade this measure.

2.4.3. Utilization Efficiency (E_U):

Is a measure of how adequately a manufacturing system utilizes its capacity, simply put it is the relation between the ideal processing rate and the actual processing rate.

$$E_U = \frac{1}{n}\sum_{i=1}^{n}\frac{TH(i)}{r^*(i)}$$

2.4.4. Inventory Efficiency (E_{inv}):

Is a measure of how adequately a manufacturing system is managing its inventories, in a perfect system both RMI and FGI would be zero and WIP would be just enough for a given throughput.

$$E_{inv} = \frac{\sum_{i=1}^{n} TH(i)/r^*(i)}{RMI + WIP + FGI}$$

2.4.5. Cycle Time Efficiency (E_{CT}):

Is a measure of how adequately a manufacturing system's cycle time is when compared to the raw processing time without including detractors.

$$E_{CT} = \frac{T_0*}{CT}$$

2.4.6. Lead Time Efficiency (E_{LT}):

It is a measure of how adequately a manufacturing system is processing jobs when compared to the quoted customer lead time. In a MTS environment this measure should be zero.

$$E_{LT} = \frac{T_0*}{\max\{LT, T_0*\}}$$

2.4.7. Service Efficiency:

E_S is the fraction of demand filled from stock in a make-to-stock environment. While in a make-to-order environment E_S is the fraction of demand filled within the established lead time.

2.4.8. Quality Efficiency:

E_Q is the fraction of jobs that go through the line with no defects on the first pass.

3. SERIOUS GAMES AS LEARNING TOOLS

As described by Rodrigues and Mackness (1998) over the past three decades many companies have tried to improve their manufacturing performance by implementing one or more different manufacturing philosophies, including manufacturing resource planning (MRP II), just-in-time (JIT) and more recently theory of constraints (TOC). It is uncommon to find a company that has successfully achieved the improvements they need to satisfy their customer requirements, [4]. Could the reason for this be the lack of understanding of the existing problems in the manufacturing system? Or might the reason be the inadequate understanding of the new approach?

Either way the central theme behind both reasons might be that the manufacturing manager never really understood what each philosophy had to offer and less likely how it could fit into his manufacturing system. Could the problem then be that the individual did not fully learn what each philosophy was about? If this were the case than would it not be a good idea to improve the way the manufacturing manager learned? This is precisely what this paper is about.

One possible approach to this problem is to incorporate games as a means to improve the learning process. Generally speaking, games give the player the sense of action in a mode that, while chiefly mental, includes the feeling of freedom, and reactive responses to physical stimuli. According to Abt (1971) games may be played seriously or casually. We are concerned with *serious games* in the sense that these games have an explicit and carefully thought-out educational purpose and are not intended to be played primarily for amusement. This does not mean that serious games are not, or should not be entertaining. If an activity having good educational results can offer immediate emotional satisfaction to the player, it is an ideal instructional method, motivating and rewarding learning as well as facilitating it, [5].

Different types of games have been used to train management in complex decision making problems such as those involved in operations management. Such problems can sometimes be described in precise mathematical terms and a mathematical model can be developed to evaluate different solutions to the identified problems. However, when these models are complex and require large amounts of calculations, computer simulations models save time and effort. The emphasis now turns to building a logical model to fully represent the understanding of the problem at hand by showing the results of different assumptions and solutions. When used by the manufacturing manager this logical model turns into a kind of game. Abt (1971) states in such a game, the participants learn the logic of the process they are studying by participating in it and seeing the consequences of their decisions, [5].

Simulation games as educational tools offer incalculable value in intuition building and problem solving. Part of this can be attributed to the game's ability to permit individual learning, this means that the results of such a tool depends on the individual's abilities. The slowest individual will concentrate on the concrete, static elements of the game. At the same time the moderately fast individual will develop concepts of cause and effect, interpret them and apply them. Finally, the advanced individuals will consider the strategic relationships of the causal chains present in the game. Because of the individual learning nature of the game, individuals have the opportunity to keep on interacting with the game permitting the slowest individuals to identify and understand the other types of relationships in the game.

Finally, since the interest of this paper is factory physics lets consider the ideas stated by Teodoro (1998). Physical sciences are the sciences of constructing models (simplified descriptions or explanations) about the physical world. In the traditional learning environment, these types of models are difficult to be mastered by many students. These difficulties can be rooted in the fact that most students do not have tools with which they can explore formal objects as “objects-to-think-with”, as “objects-to-experiment-with”. Experimentation with conceptual objects is a new kind of experiment, a conceptual experiment, only possible with computer tools, based on graphical user interfaces, [6].

4. COMPUTER BASED SIMULATION

In today’s dynamic business environment computer based simulation offers the possibility of designing, planning and analyzing complex manufacturing systems. The strengths of this type of modeling lay in its ability to represent a manufacturing system’s complex static structure as well as the dynamic behavior associated with it. According to Wang and Chatwin (2005) simulation modeling of manufacturing systems is the technique of building an abstract logical model of a real system, and describes the internal behavior of its components and their interactions including stochastic variability, [7]. This model is then represented by a computer program giving information about the system, letting us mimic the operation of the real system. One of the objectives of this technique is that it gives us the possibility to predict the behavior of complex manufacturing systems by calculating the movement and interaction of system components.

It is no surprise that all most all manufacturing systems are characterized by some sort of stochastic behavior. Common sources of randomness include:

- Arrival times of entities to the system.
- Processing times at each workstation.
- Times between repairs at each workstation.
- Times to repair at each workstation.
- Set-up times at each workstation.

If we recall, each one of these is considered as sources of variability for factory physics.

The remaining part of this section exclusively deals with the manufacturing system that was modeled, the model structure that was used and finally with the procedure used to carry out the simulation/experimentation.

4.1. System Description

Raw materials arrive at the raw materials warehouse with inter-arrival times represented by a normal distribution with mean 48 minutes and a standard deviation of 63 resulting in a high coefficient of variation (CV). Raw materials are transferred individually to the first processing station, where their processing times are represented by a normal distribution with a mean of 10 minutes and a standard deviation of 3.5 resulting in a low CV. The result of this operation is a “product”, but before being moved to the first work-in-process (WIP) waiting area a transfer batch must be accumulated. All arriving transfer batches are processed on a first in first out basis. Once processed the transfer batch is then moved to the second processing station were each unit contained in the transfer batch is processed individually, their processing times are represented by a normal distribution with a mean of 20 minutes and a standard deviation of 25.35 resulting in a high CV. Before being moved to the second work-in-process (WIP) waiting area a transfer batch must be accumulated. All arriving transfer batches to WIP area 2 are processed on a first in first out basis, once processed at this area, transfer batches are moved to the third processing station were each unit contained in the transfer batch is processed individually, their processing times are represented by a normal distribution with a mean of 7 minutes and a standard deviation of 0.5 resulting in a low CV. Before being moved to the final work-in-process (WIP) waiting area a transfer batch must be accumulated. All arriving transfer batches to WIP area 3 are processed on a first in first out basis, once processed at this area, transfer batches are moved to the fourth and final processing station were each unit contained in the transfer batch is processed individually, their processing times are represented by a normal distribution with a mean of 8 minutes and a standard deviation of 2.75 resulting in a low CV. Products are moved individually to a finished goods warehouse where they wait for the arrival of a sales order enabling the shipping of the product to the company’s customer. The inter-arrival times of incoming sale orders is represented by a normal distribution with a mean of 11 minutes and a standard deviation of 15.75 resulting in a high CV. The system receives incoming sale orders at the company’s sales office. All transfer time between system elements are assumed to be 1 minute.

4.2. Model Structure

The model was developed using ProModel Version 6.0 and is composed of the following modeling elements (see Fig.1 Model Layout):

4.2.1. Locations:

A total of 17 locations are required to model the described system and to permit the user to fully appreciate the learning objectives of the model. Among these locations are the two warehouses, the sales office, the four processing stations and the three work-in-process waiting areas.

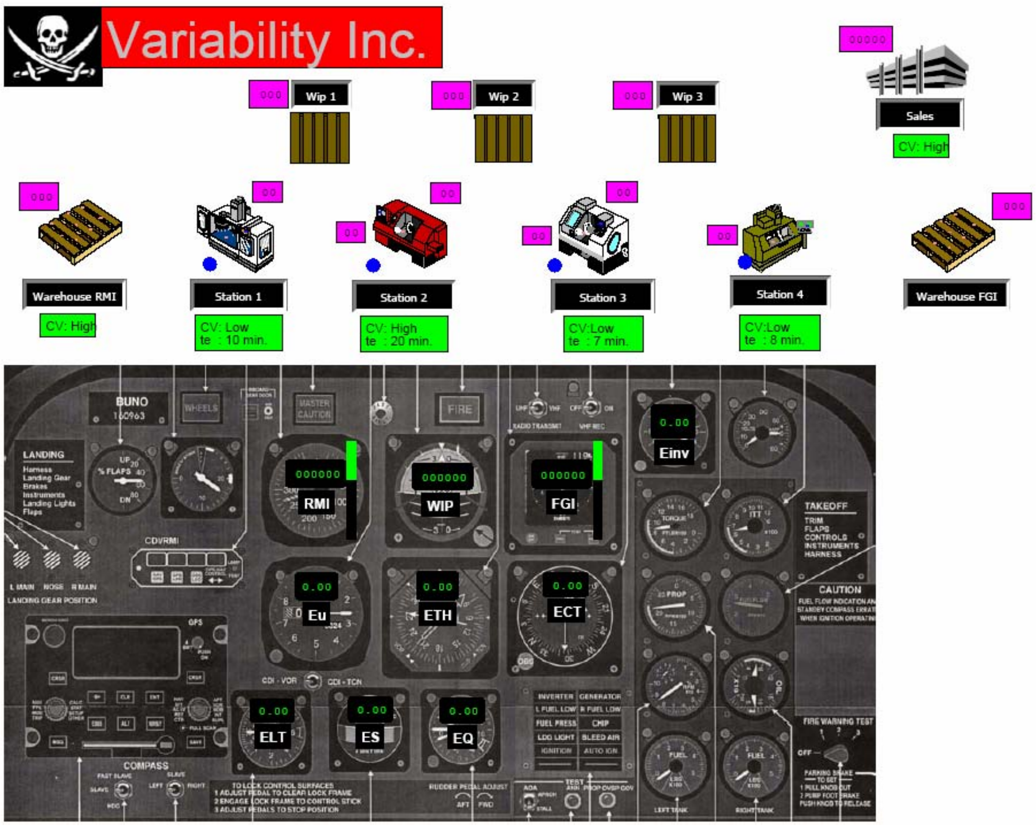


Figure No.1 Model Layout, [8]

4.2.2. Entities:

Five entities were used in order to model the described system, including raw material, product, transfer batch and sale orders.

4.2.3. Attributes:

Three attributes were necessary to determine the cycle time of each product processed through the system.

4.2.4. Variables:

A total of 41 variables were necessary to model the described system and to permit the user to fully appreciate the learning objectives of the model. Part of these objectives included permitting the user to see interactively how his actions affected the performance of the system.

4.2.5. Run-Time Interface (RTI):

A run-time interface parameter enables the user of a model to change modeling parameters without having to modify any type of program code. This ProModel feature was used to permit the student to "play" with the system, giving him the opportunity to evaluate different operating alternatives by seeing these results through five of the seven performance measures defined by factory physics. To achieve this learning objective the model required a total of eight RTI parameters.

4.2.6. Graphical Interface:

Because of the analogy used by Hopp and Spearman (2000) an image of an airplanes instrument panel was used in the simulation model. Contained within the instrument panel the student can visually see how his actions affect the inventory levels in the system. At the end of the simulation run the student is displayed the results of: throughput efficiency, utilization efficiency, inventory efficiency, cycle time efficiency and finally lead time efficiency.

4.3. Simulation/Experimentation

This simulation model was developed as supplementary study material for a graduate course in Factory Physics taught to a group of operations personnel at a multinational company operating in

Cali, Colombia. The model was designed to be used specifically with Chapters 8 and 9 from Hopp and Spearman (2000) were the main topic is the effects of variability on a manufacturing system. The primary objective with the model was to foster the students intuition capabilities, it was hoped that once he understood all of the relationships contained in the model he would then be able to "play" with certain parameters (controls) and see how these would affect the manufacturing system's results (measures). Each individual student was asked to define his business objectives before running the simulation.

The model was setup to run for one year at which time all of the results were displayed. Each student using ProModel's RTI feature was able to modify any combination of transfer batch size, processing capacity at each processing station or the capacity of each work-in-process waiting area.

5. CONCLUSIONS

This paper highlighted the importance that computer based simulation can play as a learning tool, in this case in particular as a means of developing the intuition capability suggested by factory physics as an important skill for a manufacturing manager. To demonstrate this importance a simulation model was developed and applied as part of a graduate course in factory physics.

From an academic point of view it can be concluded that combining such a computer based simulation model as the one described in this paper, with the traditional learning process of in-class lecture and reading assignments is a powerful strategy to be used to achieve the established learning objectives.

In this case in particular it was demonstrated that the use of the simulation model enhanced and accelerated the student's ability to learn the following:

- To see the system from a holistic point of view and not giving so much importance to the individual elements of the system.
- To identify and value the relationships and interdependencies between the individual elements that makes up the system. An example of this includes understanding how the variability present in one element can propagate to the rest of the system.
- More importantly, in this case was the development of the student's capacity to use intuition to analyze and plan changes in a given manufacturing environment. This means that when the students were confronted with a given set of operating conditions they were able to use their developed intuition to propose the possible outcome, before running the simulation model. The model was then run and gave the expected results. In those cases were the results did not coincide with the proposed outcomes the students were able to identify the reason or reasons why there was a discrepancy.

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Biography

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