A Model for Human-like Reasoning in Programmable Controllers

Tom Keeley
President
Compsim LLC
Brookfield, WI 53045
http://www.compsim.com

Helena Keeley
CEO
Compsim LLC
Brookfield, WI 53045

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ABSTRACT

The rate of technical advancements in Programmable Controllers has slowed over the past several years. Vendors have consistently followed the trends of smaller, cheaper, and faster. They have pursued alternative architectures and repackaging alternatives to redefine solutions to the same problems they have been addressing for the past 30 years. Holonic manufacturing and agent based systems have been suggested to address discontinuities in the manufacturing process. In very few cases, however, have the Programmable Controllers been asked to take on more of the management functions that are usually left to human operators and operation supervisors. This provides an opportunity to integrate judgmental reasoning directly into the Programmable Controller where access to information is closer to the real-time environment. By placing judgmental reasoning at the Programmable Controller level, the management decisions can be made much more quickly.

This paper proposes a subjective decision-making model that can be integrated directly into conventional Programmable Controllers, through the use of a new programming paradigm. It does this without the need to change the Controllers themselves. The Programmable Controllers can then take on qualitative judgments such as Safety, Risk, Survival, Profitability, and Asset Management in a manner that can be audited by operations management. Because the manufacturing process requires completely explainable and auditable designs, this approach provides a dynamic graphical language that can be audited. If cognitive capabilities were added to Programmable Controllers, it is very likely that PLCs will suddenly have brand new applications in totally new market areas.

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INTRODUCTION

Control systems for manufacturing operations have been defined as “large, complex artifacts which are designed to perform a clearly-defined task in a well structured, standardized environment”.[1] This definition suggests little opportunity for adaptive behavior.

The vast majority of these systems today utilize Programmable Logic Controllers (PLCs) to orchestrate the operation of equipment and coordinate the movement of material, especially in discrete manufacturing areas. These discrete manufacturing operations are identified with a sequence of discrete steps that must be performed to produce or manufacture products. To a somewhat lesser degree, PLCs are used in the batch and continuous manufacturing systems in areas where sequential logic is needed.

In these systems one can define boundaries in terms of responsibility. The PLCs have the responsibility for processing the repetitive input and output functions according to absolute rules defined with any of a number of programming languages (Ladder Diagrams, Sequential Function Charts, Function Blocks, Structured Text, and Instruction Lists[2]). Many PLC manufacturers have included specialty cards that implement personal computer (PC) functionality on the same backplane, thus enabling the integration of data processing functions as part of the automation process. The next generation of system configuration has been the focus of IEC-61499[3], which focuses on lifecycle programming, where functionality is defined from a higher level and distributed appropriate devices. Humans interact with these systems through Human Machine Interface (HMI) stations, push buttons, etc.

Information can flow into and out of these control systems from among others ERP (Enterprise Resource Planning) and MIS (Manufacturing Information Systems).

Humans participate in the manufacturing process by providing services that are not provided by hard automation. For example, humans may load and operate machines. They may supervise the entire operation. It is this supervisory role that is addressed with this paper.

One negative aspect of automation systems with “humans in the loop” is that humans have been given responsibility for overseeing very complex systems. These systems may have thousands of inputs and outputs of various types. Massive amounts of data items are generated. Numerous tools are attached to these systems to display system status and warn the human operators and supervisors of problems that may need attention to support this responsibility. But it is still left to the humans to make the appropriate judgmental decisions to control the systems. Human error or human inattention, may cause significant problems to the enterprise (the ultimate beneficiary of a manufacturing system), because some of the more critical issues may occur very infrequently. It has been estimated that up to 90% of all workplace accidents identify human error as a cause.[4]

This paper focuses on judgmental decisions that have been relegated to the human components of the manufacturing system.

CONVENTIONAL PLC SOLUTIONS

PLCs have evolved from relay ladder logic replacement of physical relays to more complex discrete applications including support for analog input/output (I/O). In the 1980's and 1990's more custom interfaces were developed, network architectures were created, and new programming languages were developed.

The conventional application of PLCs in factory environments has dealt with discrete manufacturing processes. For years, the state-of-the-art was identified with 'Proportional, Integral, Derivative' (PID) algorithms and the "tuning of PID loops". These applications have tended to focus on the dynamics of isolated control signals. Recently, the integration of motion control instructions into sequential logic systems have allowed slightly more complex systems to be developed.

Manufacturing architectures have evolved from massive centralized control, to hierarchical tree models, to distributed levels of control, and recently, to flat distributed architectures across a TCP/IP protocol.

In conventional alarm systems the problem of diagnosis is left completely to the operator. The alarm patterns are situation dependent and do not include any clues as to how to interpret the available data. The operator has to perform a very complex inference process where measured data and alarms are combined with his / her knowledge of process functions and properties. This bottom-up approach to diagnosis excludes the explicit consideration of system information which is known to the designer, such as the purpose of subsystems. Conventional alarm systems are situation dependent and their design requires specification of dynamic, multi-variable, non-linear, inter-related information sets.[5]

To some extent, the addition of PC functionality and specialty cards supporting fuzzy logic and neural nets have provided 'platforms' for addressing more complex system issues. With all of these developments, however, the focus has not significantly changed. The overall objective of PLC vendors has been to create control elements that can work together in a coordinated fashion. The responsibility of the PLC has remained relatively the same, with the exception that it is now responsible for the concentration and distribution of messages in addition to its discrete logic control functionality. Relatively little focus has been applied to automating the "human reasoning" component of the automation processes.

HUMANS IN THE LOOP

Like the PLC, the responsibilities of humans in the factory automation system have also remained constant. Humans play the part of adaptable machines where it appears impractical to automate the system. In this case they are the "cost effective robots" that are taught to perform repetitive tasks. In this way, they are the ultimate tools in flexible manufacturing today.

In their other role, that of operator or supervisor, they make the judgmental decisions regarding how the factory operates. In this role, the humans utilize their training and experience to monitor equipment operation and adjust parameters to tune the process. They control material flow and schedule maintenance. They are responsible for the overall performance of the systems under their control.

To perform this operator / supervisor role, the humans make subjective judgmental decisions. One might suggest that this is the weak link in the manufacturing process. As an example, one would suggest that any manufacturing process that created products with the variability of humans (i.e. manufacturing humans with their character flaws, lack of attention, poor judgment, lack of consistency, etc.) would be an unacceptable process. Even mechanized farming has progressed to the point where the plants[6] and animals are manufactured[7]. In this light, while one can control processes and duplicate machines to build consistent products, one cannot duplicate perfect human models (yet) to manage or supervise production lines in the best available way. Similarly, since one can build machines according to well understood plans, one can improve the designs over time so they can perform better. With humans, industry starts the process over with every operator, attempting to train them to perform in the best way possible. Even using improved training techniques, industry starts over with every employee.

JUDGMENTAL DECISIONS

Before this paper discusses how to improve the process, it is appropriate to describe the types of decisions or actions that the human performs when he/she is acting in the operator / supervisor role. This paper will define these types of decisions or actions as judgmental or subjective in nature. This paper does not consider the absolute rules that must be performed, as these are just the components of the job where humans are being used as “flexible robots”. In these cases the decisions and actions are not subjective.

The judgmental problems involve the interpretation of information. The result may be to take either one of several actions, or several actions from among many. Also, each action may need to be executed entirely or partially (relative or scaled actions). These decisions may also have a time element. This could mean that an action will have an optimal time to be performed.

To address these judgmental issues, the human balances the impact of various “relative actions”. The human orchestrates the responses, much like a conductor controls an orchestra. In some cases, there may be just a few options under the operator’s control. In others, there may be many options.

With humans in the loop, systems engineers responsible for building the automation systems / production lines, attempt to build safety mechanisms into the design to keep the human participants from making inappropriate decisions / actions. In this way they attempt to protect the humans, the machines, and the production from damage. These design models, however, focus on survivability and not on optimization. The judgmental decisions commonly assigned to human operators focus on optimal performance of the production system (inventory management, performance modification, asset management, diagnostics / prognostics, etc.). The human is making decisions based on risks versus reward. The human is *attempting* to apply written company policies that *attempt* to describe how to respond to situations that might be encountered.

NEW CONCEPT

Given that humans are the weak link in many manufacturing / production systems, this paper will focus on a mechanism that will allow some of the judgmental decisions presently delegated to humans to be configured in conventional PLCs. The objective is to address issues related to human inattention, poor judgment, personal biases, etc., in the manufacturing process. The objective is then to replace those undocumented, unexplainable decisions and actions with a model that can address the same subjective / judgmental issues with a controlled process that is completely explainable and auditable. The objective is also to provide a model that is adaptable to external information and extensible as new expertise or knowledge becomes available. The ability to provide a model that can be replicated across the enterprise in a cost effective manner can then be realized.

First, this paper will discuss a technology that can be used to model human-like decision-making. Then it will describe how this technology can be deployed in PLCs. Finally, it will address why this new PLC model is superior to one based on humans; specifically in the areas of stability, repeatability and its ability to be audited and enhanced over time.

The objective of this concept is to extend the capabilities of conventional PLCs to be able to take on some of the subjective reasoning responsibilities commonly delegated to human operators and supervisors. By automating these processes, industry can reduce the weak links in the manufacturing processes that are prone to human error, poor judgment, personal biases, or a person just having a “bad day”.

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KNOWLEDGE ENHANCED ELECTRONIC LOGIC (KEEL®) TECHNOLOGY

KEEL is an umbrella term defining a collection of services that allow human-like reasoning to be embedded in devices and software applications. This technology is suggested as an option for manufacturing systems when judgmental decisions or subjective actions are required as part of the process. When KEEL Technology is discussed in relation to a PLC, it is like adding a “right brain”[8] component to the PLC’s existing “left brain” component. In humans, the left brain is associated with numbers, language, fixed rules, etc. The “right brain” is responsible for images, interpretation of information and subjective judgments. Adding KEEL technology to PLCs provides the PLCs the ability to address judgmental subjective issues presently delegated to human operators and supervisors.

KEEL technology incorporates a graphical methodology for defining human-like reasoning that maps closely to the process that the human’s right brain uses to evaluate information. In judgmental decisions, the “importance” of multiple information items is balanced to determine the best overall set of actions for the system. The act of making a judgment decision is complex, because it needs to address multiple problems simultaneously and consider the interactions that may exist between them.

For example, an operator may make a judgmental decision on how fast to run a machine. That decision might be based on demands to increase production, to avoid damage to the equipment, to maintain quality, etc. The operator balances risk and reward in making the determination of how fast to operate the equipment. A supervisor may stress production commitments and suggest that the operator run the equipment faster. The operator may review the risks and rewards and adjust the performance accordingly. In a manufacturing line, this action may not be auditable or explainable, and new problems might be generated. In this example, who is responsible if the machine breaks? Why was this allowed to happen? What can one do to insure it doesn't happen again when the pressures to produce more with less recur?

With KEEL technology, the reasoning model is created off-line, just like the primary PLC program. A graphical language is used to define the reasoning policies. The size of graphical elements defines the *importance* of information. Wires (lines) are used to indicate *relationships* between information items when one decision or action impacts another (or others). KEEL technology is in the expert system domain, since it requires a human expert to define the rules. During the development of the reasoning model, the designer tests the logic by stimulating simulated inputs and observing outputs or graphing the interaction between various items. Because the language is dynamic, the designer gets immediate feedback relative to the changing importance of information and the dynamic relationships. The designer can "see" the system balance alternatives and "see" the relative (analog) output control signals that define the relative decisions.

Figure 1 shows a language segment with three inter-related decision components. The bars at the top are outputs that can be used external to the reasoning engine or they can be intermediate collection points for later processing. The first (left most) decision component has six independent inputs shown below it: three of which drive the decision (green) and three of which block the decision (red). The integration of the inputs of the first decision component *controls the importance* of the second decision component, which has two supporting and one blocking input. The integration of the second component *contributes to* the third decision component by driving one of its inputs. This figure is not intended to demonstrate any specific application, but only to show some of the basic concepts.

Complex problems are addressed by humans as they consider different actions related to different inter-related issues. Simultaneously they are considering how each of those actions might influence the other actions. Humans "balance" potential actions (for as long as they feel appropriate) until they determine the best collective courses of action to take. In cases where there is no time penalty they may stop thinking about the solution when they feel they have considered the best solution. When there is no apparent value to make a decision, they may just continue to think (worry) about the situation or they may just ignore the problem.   With KEEL technology, this "balancing" is accomplished during a "cognitive cycle". At the end of the cognitive cycle a decision or action is ready to be accomplished. While it is not described in this paper, there is often an optimal time to make a decision. The graphical language supports Time Utility Functions (TUFs)[9], so time and distance can be just like any other piece of information to evaluate subjective situations.

KEEL IMPLEMENTATION IN A PLC

KEEL designs are packaged as PLC Structured Text, when targeting conventional PLCs. When the target platform is a PC specialty card, the KEEL design might be packaged as C, Java, C#, or Visual Basic. After the designs are completed and tested using the KEEL dynamic graphical language, a menu option in the toolkit allows the designer to select the language of choice. Unlike conventional languages programmed by humans using language constructions focusing on program flow (IF-THEN-ELSE…), they are not processed as just a single series of sequential instructions. KEEL engines process information iteratively until a stable answer is achieved. They process complex situations in the same manner that has been described above regarding how humans solve complex multi-dimensional problems. This is called a *cognitive cycle* in the context of KEEL Technology. The KEEL engines balance alternatives to achieve the best action at that instant in time. Because this cognitive processing is an iterative process, it is not conducive to the sequential processing normally attributed to PLC "I/O scans". A KEEL process can be said to be deterministic, however, because there is a known "maximum" processing time.

Many of today's PLCs support various techniques for parallel processing. Sequential Function Charts are one way to synchronize processes. Using this approach, the task with the KEEL Engine could be accomplished in one side of the chart while the I/O could be accomplished in another. Some PLCs support multi-tasking. This may be an even better approach for handling KEEL Engines within the existing PLC architecture.

While it may be possible to execute KEEL Engine blocks as a sequential part of a program scan, this is probably not the best approach since the balancing function is not deterministic (from a timing standpoint).

ADAPTABILITY

One of the key functional requirements for incorporating human-like reasoning into the PLC is its ability to exert reason when determining a course of action. KEEL technology supports this requirement by allowing external signals or commands from a higher authority to modify how the KEEL engine will interpret the data. This external control signal might be just one of several factors that could modify the performance (rules) of the device. For example, a pump may adjust its speed based on the viscosity of the liquid it was pumping. An external vibration sensor may command the pump to adjust its rule-base because of vibration. Two independent functions could work together to perform the desired function in the best way using this method.

EXPLAINABLE AND AUDITABLE

PLCs are used to control devices in high risk environments. As such, the logic used to control those devices must be explainable and auditable. The same rule must be applied when defining the human-like judgmental-reasoning in these high-risk environments. Should a problem arise, it must be possible to review the design and diagnose any action. This is the service that is not really available with humans. The human written or verbal language is ineffective in describing why any judgmental action is performed at any instant in time to the level of detail that industry expects out of a machine (or computer).

The design for the human-like reasoning must be able to be tuned or fixed without undue time and effort; just like the basic PLC program. It is mandatory that actions taken by the PLCs be auditable. Decisions / actions of the PLC should be logged and made available for humans to "see" why an action was taken. Similarly, inputs to KEEL reasoning should be logged, this data may be viewed in the development environment where the user can see exactly why any judgmental decision (or relative action) is taken.

STRATEGIC THINKING – GOAL SEEKING

One of the functional requirements of a human-supervised manufacturing system is to be able to address goals. In a KEEL based system, these strategic goals are contributing factors to actions. It is these strategic values that are used to adjust the rules so when the system balances itself, the strategic goals participate in the decision-making process. Every human develops their own values and has their own personal objectives. With human judgmental decisions, these personal drivers are almost never exposed or evaluated. Some of these objectives may be counter-productive to the goals of the enterprise: wealth, junk food, the desire to play rather than work… When manufacturing systems are constructed of devices with human-defined rules, it is possible to create systems with well understood and documented rules. It is possible to build systems that consider their own safety or survivability as part of the policies. In this way, PLCs can coordinate operation of work cells according to policies developed by the Manufacturing Engineering function.

SAMPLE PROBLEM

Referring again to our production problem where the operator is asked to increase production. The operator is responsible for the operation of the equipment. The operator has been trained on safe operation of the equipment. The operator is given work orders to define what is expected for that day's production. The operator controls the speed of the machine. By increasing the speed, more parts are produced, but the quality degrades, and wear and tear on the equipment increases.

To pose one scenario: During the day, the operator's supervisor comes by and informs the operator of the need to increase production because of a new order. The operator increases the speed a little bit and production increases. The operator detects a new vibration in the machine being used to produce the parts. After ignoring the vibration for a while a maintenance technician is called. Production is stopped while the technician looks over the system. ………

In this example, the humans made a number of judgmental decisions: 1. The supervisor made a judgmental decision to try and escalate production by telling the operator of the new order. 2. The operator made a judgmental decision on how much to adjust the machine speed by balancing risk against the need to increase production. 3. The operator made another judgmental decision relative to the amount of vibration which justified calling the service technician. 4. The service technician made a judgmental decision about whether to stop production to analyze the system.

None of these decisions are auditable in terms of what one would expect of an automated system. The reasoning behind them is not transferable to others, because they cannot be explained in mathematical terms. There is little opportunity to upgrade or refine the decision-making process, since the existing process cannot be explained or audited.

By introducing KEEL technology into the system design as shown in Figure 2, the importance of increasing production would be supplied to the system as a weighted value. This value would be integrated into the performance calculation according company policy. This company policy would take into account known risk of increasing machine speed (Figure 4). A separate segment of the KEEL engine would be monitoring diagnostics (vibration in this example). The impact of vibration on Production Value is shown in Figure 3. Again, according to company policy, the service technician would automatically be called when a certain level of vibration was detected. This is shown in Figure 2 when the vibration reaches a normalized value of 60. At the same time the machine speed or other control parameters might be immediately (or continuously) adjusted based on vibration feedback from the machine (again, according to company policy). This is also accomplished in the Figure 2 design. Finally, the decision by the service technician to take the machine out of production for examination might be indicated by the machine itself, rather than waiting for the decision by the service technician. In this design the increase in vibration is fed back into the speed control loop and automatically reduces the machine speed. Figure 5 shows a 3-D graph of the production value as speed is increased and as detected vibration increases. In all cases, because the policy processing is integrated into the PLC, it can be copied and distributed to other locations. If it is found that the policy needs to change, it can be updated to match the needs of the enterprise. In all cases, the reasoning can be explained and audited.

Referring to Figure 2, it took approximately 15 minutes to develop this sample model. The output of the model is translated to a text file in PLC Structured Text format (or C, Java, Visual Basic, or C#...). The systems engineer would copy the text of this file into the appropriate PLC programming tools for the PLC being used.

SUMMARY

“Six Sigma”, “The Baldridge Award”, “Quality Function Deployment”, “Statistical Process Control”, and “ISO 9000” are all programs focused on increased quality that target the manufacturing process. When the manufacturing process includes humans in the role of supervisors and operators that make judgmental decisions as part of their responsibilities, the systems suffer from the frailty of the human condition. Humans are not machines and do not perform with the same level of consistency, even with the tools that are available to them today. Their judgmental decisions are not auditable in the same way that machines are subject to audit, because the human written and verbal language is always open to interpretation. Their reasoning cannot be documented as a formula that can be decomposed and evaluated.

Some of the judgmental decisions and subjective actions can be incorporated into the system design by incorporating KEEL technology in PLCs. These decisions and actions can then be explained and audited by reviewing the logic in the KEEL graphical language. This can be done without reverting to complex hard-coded mathematical solutions. The language is explicit, in that once an audit indicates that a change is required, the reasoning model can be corrected and extended if necessary.

Manufacturing systems need to process conventional hard-coded logic to address the deterministic situations that exist in any control system. These same systems can benefit from judgmental reasoning when they are required to adapt to changing demands that are caused by component failures or by changing business drivers. KEEL technology is suggested when judgmental decisions can be automated. In these cases, *completely explainable actions* are required. The development environment, which allows immediate feedback into the design process, is an added benefit when the economics of managing any new technology needs to be considered.

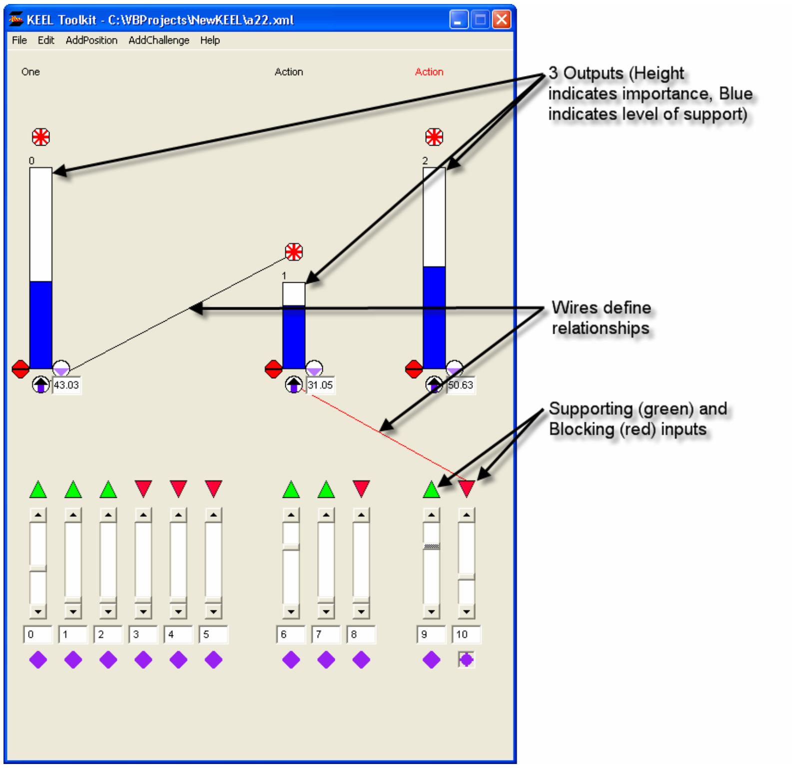

FIG. 1 – GRAPHICAL PROGRAMMING LANGUAGE

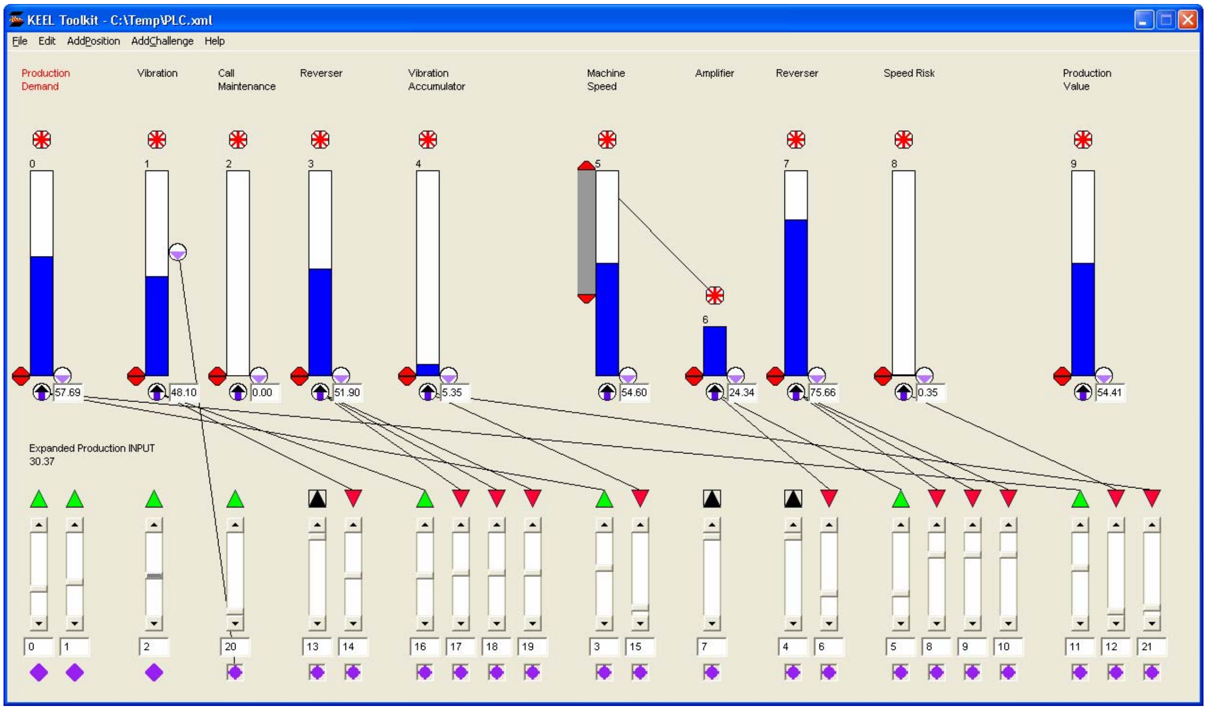

FIG. 2 – SAMPLE PROBLEM – POLICY ENCODED IN KEEL DYNAMIC GRAPHICAL LANGUAGE

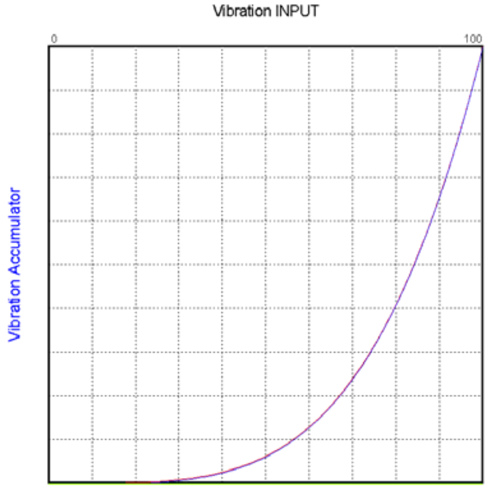

FIG. 3 – VIBRATION IMPACT ON MACHINE SPEED AND PRODUCTION RISK

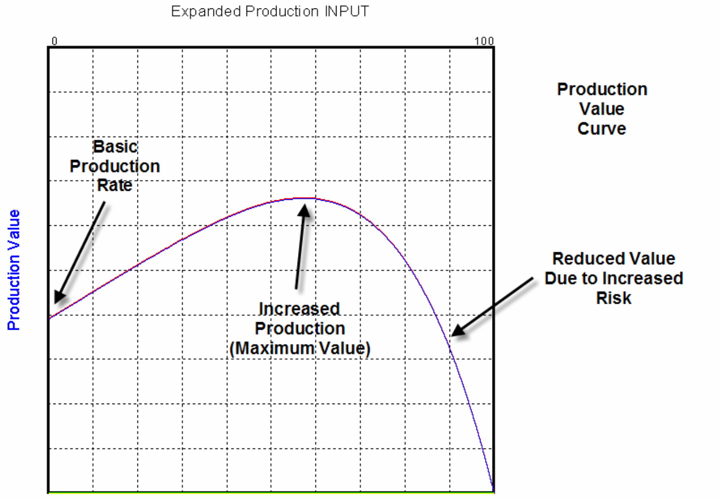

FIG. 4 – PRODUCTION VALUE CURVE

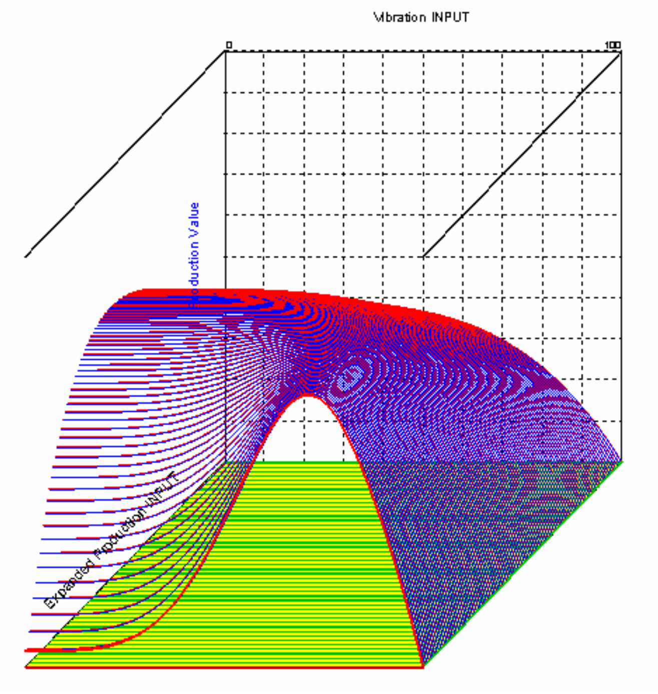

FIG. 5 – POLICY GRAPH FOR IMPLEMENTATION IN PLC

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