Intelligent Industrial Processes

Systems Engineering for IIP

Luleå University of Technology
Abstract

Intelligent Industrial Processes do not naturally occur; they are engineered. This is a white paper that describes the role of Systems Engineering in Intelligent Industrial Processes. We first try to get a grasp of what we mean with Intelligent Industrial Processes and Systems Engineering. The state of the art for Systems Engineering is reviewed with systems life cycle processes and Model Based Systems Engineering (MBSE). It is followed by current problems in process industry and presents MBSE as a partial solution for an industrial framework towards “Intelligent” industrial processes. The white paper clearly shows that a lack of consideration of Systems Engineering in industrial processes leads to a deficiency in understanding industrial processes and impacts its leadership. With an established need for Systems Engineering, a SWOT analysis and a triple road map for LTU is presented including potential collaborations.

Keywords: Systems Engineering, Industrial Processes, Life cycle, MBSE, FMEA, Operation, Maintenance.
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1 Introduction

Luleå University of Technology and its faculty board have set up nine areas of excellence in research and innovation. One of these areas of excellence is Intelligent Industrial Processes (IIP). The herewith document is a white paper presenting Systems Engineering as a key enabler towards a potential set of Intelligent Industrial Processes by 2030. The document is part of the gray literature put forward on the onset of the area of excellence to coordinates the different research areas at Luleå University of Technology (LTU) and build a concrete strategy.

Quoting IIP’s web page, the area of excellence is introduced with a need and a means as: “a versatile and competitive industry is important for Sweden’s and Europe’s future status as new players are emerging. To secure our position, constant improvement and development of industrial processes are required in order to increase productivity while reducing the pressures on the climate and the environment” [2]. This vision can be restated as our leading industries must survive and the win-win scenario is for LTU to support industries to lead, starting with those close to the university and expanding outwards.

The choice by the university and its faculty board to create these nine areas of excellence was not random but was based on a solid foundation of experience within the university. These areas of excellence are not independent and one easily finds relationships between them. One example related to IIP is the Future Mining, which has stakes from prospecting and extractions to the processing of the ore. Another example is the Enabling Information and Communication Technology area (EICT). The existence of an EICT white paper within the IIP’s gray literature makes this overlap evident. This claim being supported as well by literature, which points ICT as a key modern enabler in industrial automation.

For IIP, one of these solid foundations is LTU’s research centre ProcessIT Innovations. Quoting from its web site: “ProcessIT Innovations is a collaboration centre in northern Sweden. The strategic concept of ProcessIT Innovations is to bring together the functional process and engineering industry in the region with ICT services in universities and industry” [3]. ProcessIT Innovations has a strong base of committed stakeholders, which is clear through its financial backing, not only from industry but funding bodies also. In 2003, ProcessIT Innovations was awarded the title of Vinnväxtrännare by VINNOVA¹, thereby being guaranteed financial support over a period of ten years.

In its Annual Report for 2013 one reads: “Business year 2013 has been a very successful year for ProcessIT and its partners on account of the launch of two very comprehensive initiatives. This includes the national

¹The Swedish Governmental Agency for Innovation Systems
strategic innovation area Process Industrial IT and Automation, PiiA, and the extensive European initiative Arrowhead, Europe’s largest research project in the development of automation for manufacturing, energy and process industries. ProcessIT Innovations has actively contributed to both of these initiatives in order for them to be realized. These investments are extremely large, with a budget of SEK 220 million for Process Industrial IT and Automation and about €68 million for Arrowhead”. Arrowhead’s vision is to enable collaborative automation by networked embedded devices. One hindrance is the need to enable the interoperability and integrability of services provided by almost any device along with complete security. In other words, devices such as sensor and actuators communicate with each others to efficiently get the “process” done. This is something that arguably has been done for a long time. The new twist comes with the Enabling ICT where the information is distributed everywhere as well as the processing, analysis, decision making or computing. The grand challenge is then to coordinate and communicate with the stakeholders (from raw resources to finished products, suppliers and customers, as well as the environment) to achieve the best results.

Having set the context of why LTU has Intelligent Industrial Process as an area of excellence, we need to focus on the research and its road-map. Different researchers have been working on essential building blocks towards this utopia. The research topics include automatic controls, industrial electronics, embedded systems, computer communication and computer science [4, 5, 6, 7]. IIP presents itself as using of its multidisciplinary strengths and the networks within which LTU has a leading position. Systems Engineering is the research topic that can agglomerate the multidisciplinary strengths and stakeholders’ interests to develop Intelligent Industrial Processes.

This white paper reviews the field starting with the interpretation of the words Intelligent Industrial Processes and Systems Engineering. It is followed by the state of the art in Systems Engineering. We then look at how Systems Engineering can contribute to IIP through problems and their industrial relevance. This is done in conjunction with other white papers within IIP. Subsequently, three coincident road-maps are proposed to develop Industrial Intelligent Processes along the three pillars of the university: research, education and support to industry. The conclusion that Systems Engineering is essential to IIP’s goals ends the white paper.

2 Description of the Field

This white paper discusses several disciplines, with a special focus on Systems Engineering. Before jumping into Systems Engineering, the application context needs to be clarified: what are Intelligent Industrial Pro-
cesses?

2.1 Intelligent Industrial Processes

This clarification has been addressed by all grey literature in this area of excellence. Beginning with the noun rather than the adjectives, “Processes” are a set of interrelated or interacting activities or steps to achieve an actual end. If this end is not accidental or involuntary, it can and should be specified. There is an inherent need for specifications, which Systems Engineering inherently accounts for.

Adding one adjective and quoting from the white paper by Dependable Communication and Computation we can continue with Industrial Processes: “The traditional definition of an industrial process tells that the industrial process is a systematic series of mechanical or chemical operations that produce or manufacture something. Another definition of a similar kind tells that the industrial processes are procedures involving chemical or mechanical steps to aid in the manufacture of an item or items, usually carried out on a very large scale” [5].

One should reflect on the fact that such industrial processes bring together many stakeholders of different disciplines. They each have something to gain and do not necessarily have the same stake. They might conflict with each other. Systems Engineering processes and tools are capable to bring the complete solution to the overall objective while crumbling conflicts with mutual understanding.

Finally, adding the second adjective makes the name most innovative: Intelligent Industrial Processes. The adjective Intelligent is very often used nowadays; so much that some might feel that it lost its meaning. What is meant here is that the industrial process should handle disturbances in inputs and environmental influences as well as component failure. By handling the disturbance we can expect processes to operate at the best efficiency possible and provide information to the operators of the problems encountered. In some cases, the system can reconfigure itself. One cannot however expect that the system should assemble itself or engineer itself because it is called intelligent. The systems engineering tasks remain that of human stakeholders, which are from different disciplines and have a stake in the industrial process. The challenge is then to continuously coordinate these different, and sometimes conflicting, interests and skills to achieve all the primary goals.

2.2 Systems Engineering

Initially, the term Systems Engineering might be just as vague as Intelligent Industrial Processes. But both expressions can be defined or at least one’s interpretation of them can be stated.
We can begin to ask “what really is a system?”. One definition is: “a combination of interacting elements organised to achieve one or more stated purposes, an integrated set of elements, subsystems, or assemblies that accomplish a defined objective. These elements include products (hardware, software, firmware), processes, people, information, techniques, facilities, services, and other support elements” [8]. Examples would be an air transportation system or an industrial process. A system is a big bag filled with components that hopefully will co-exist and cooperate for a purpose. In nature, we can point to a singular cell organism, a weather system or an ecosystem as systems. To be relevant to IIP, we need to consider man-made systems, for example, a factory (or building filled with components), which can be more or less effective and efficient. These two characteristics, effective and efficient, are never an accident, they are engineered. . . , the question being: “how?” The term “Systems Engineering” is not old, nor fashionable buzzword. It can be traced to the 1940’s at Bell Labs. To illustrate what it is about, NASA’s Apollo program is usually cited. This is the program that brought humans to the moon. Errors in the execution of any spaceflight are not allowed. For example, with Apollo 11, the rocket and the spacecraft with its three modules had to work together with no flaws and without waste. A trial and error development were not possible. A short definition of Systems Engineering is: “Systems engineering is a methodical, disciplined approach for the design, realization, technical management, operations, and retirement of a system” [9]. A longer definition is: “Systems Engineering (SE) is an interdisciplinary approach and means to enable the realization of successful systems. It focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, and then proceeding with design synthesis and system validation while considering the complete problem: operations, cost and schedule, performance, training and support, test, manufacturing, and disposal. SE considers both the business and the technical needs of all customers with the goal of providing a quality product that meets the user needs” [8]. Systems Engineering has emerged within industry to address system complexity, inter-disciplinary communication and the need to clarify the customer’s needs. Systems Engineering is also creeping into education and academics. It is this interdisciplinary aspect of the subject that might create this vagueness about itself. Engineering education is hard enough on one topic. Having good educational program on several topic is quite harder. Several university have recognised a need for that and offer Systems Engineering programs. The list of schools awarding Systems Engineering degrees is not so long [10]. LTU does not have a Systems Engineering education although it
has a “Systemteknik” department.

Professionally, there has been a need for Systems Engineering recognition. It is only in 1990 that a professional society has been formed for Systems Engineering. It was named the National Council on Systems Engineering (NCOSE). It was five years later, in 1995, that it became an international society with the current acronym of INCOSE. The IEEE has a Systems council that collaborates with INCOSE.

When attending a Systems Engineering conference, a surprising population is the military. This seems odd at first, but upon reflection it does make sense. For example, in a military mission, all the “components” have to be at the right place at the right time for the mission to succeed. All “components”, including personal, must be ready, reliable, efficient and effective. The US Department of Defence (DOD) published in 2001 a book on Systems Engineering Fundamentals [11]. In it, we can discover a whole process around Systems Engineering and its management. Figure 1 depicts the DOD’s view on System Engineering Management.

![Figure 1: US DOD’s 3 Systems Engineering Management Activities [11].](image)

As the figure shows, there is a tight connection between Systems Engineer-

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2 More correctly nowadays: Institutionen för system- och rymdteknik, which translated in English is the Department of Computer Science, Electrical and Space Engineering.

3 The Institute of Electrical and Electronics Engineers
ing and project management, especially obvious during the initial phases of the system’s life cycle. NASA’s view on the topic is shown in figure 2 [9].

![Figure 2: NASA’s view on SE and project management [9].](image)

Since the 1990’s, much more work has been published on Systems Engineering. INCOSE has been publishing a Handbook on Systems Engineering in multiple, which we can use when beginning to review the state of the art in the Systems Engineering. Another excellent publication on the topic is NASA’s Systems Engineering Handbook. For a more gentle introduction to the topic, one can turn to the eBook: Systems Engineering for Dummies sponsored by IBM [12].

It is therefore appropriate to undertake a brief review the state of the art of Systems Engineering.

### 3 State of the Art

The state of the art is, in this paper, limited to Systems Engineering Handbooks and Standards with support from scientific publications towards life cycle processes as well as Model Based Systems Engineering.
3.1 Handbooks and Standards

The INCOSE has been publishing the Systems Engineering Handbook [8]. The current version is 3.2.2 and the long awaited version 4 should come out in the spring of 2015.

Version 3 tries to represent a paradigm shift toward global industry applications consistent with the Systems Engineering Vision. The handbook aims to provide an updated description of the key process activities performed by systems engineers. Its primary audience is the new systems engineers or engineers in another discipline who need to perform systems engineering. It is also meant to be a reference book for the experienced systems engineer.

The descriptions in the SE handbook show what each systems engineering process activity necessitates, in the context of planning for design, performance, reliability and affordability to all stakeholders. It is a general process, which has to be adapted to each system and management. In some projects, a given activity may be performed very informally as on the back of an envelope. In other projects, it might performed very formally, with interim products under formal configuration control. The handbook is not intended to advocate any level of formality as necessary or appropriate in all situations. As in project management, there is a balance between what is really needed from the extremes of over doing the details (waste of resources) and doing nothing (an assurance to failure). This balance needs to be continually assessed for each project as well as for each system.

Following the discussions on life cycle stages, the handbook focuses on the life cycle processes. These processes can be grouped into five categories: technical, project, agreement, organisational and tailoring processes. Version 3 might not have achieved a full consensus on the SE process, especially towards certification SE engineers. It is for this reason that version 4 is anticipated and the rumours are that it is an improvement.

In NASA’s SE handbook, one is quickly referred to the life cycle of the system [9]. “The objective of systems engineering is to see that the system is designed, built, and operated so that it accomplishes its purpose safely in the most cost-effective way possible considering performance, cost, schedule, and risk”. NASA’s handbook really provides a description of the Decision Analysis Process, which includes alternative tools and methodologies. Similarly to the INCOSE handbook, systems costs are addressed through analysis. INCOSE’s SE handbook relies on the ISO/IEC 15288 standard. The ISO\textsuperscript{4}/IEC\textsuperscript{5} 15288: Systems and software engineering - System life cycle processes is additionally sponsored by the IEEE [13]. Its abstract states: “This International Standard establishes a common process frame-
work for describing the life cycle of man-made systems. It defines a set of processes and associated terminology for the full life cycle, including conception, development, production, utilization, support and retirement. This standard also supports the definition, control, assessment, and improvement of these processes. These processes can be applied concurrently, iteratively, and recursively to a system and its elements throughout the life cycle of a system.”

One can always wonder why such a focus on life cycle processes. Garry Roedler, a senior program manager of Systems Engineering at the Lockheed Martin Engineering Process Improvement Center, has a slide presentation with the interesting title “What is ISO/IEC 15288 and why should I care?” [14]. It is when we care about the life cycle processes in industrial processes that we can achieve effective and efficient industrial processes, i.e. in our case intelligent industrial processes. Embedded in these processes is the refinement of concept and requirements to details of how a system is build followed by tests to validate the sub-systems and then the whole concept and verify that regulations are still met. A model that has been an iconic illustration within Systems Engineering is the V-model [15]. During the life cycle processes, the V-model is not static but continuously iterated as it is a tool. One problem that one quickly faces, as the complexity of the system increases, is that the difficulty of handling information and documentation. How should we handle documents such as requirements, designs, changes, validations without spamming the stakeholders or missing out on information?

![Figure 3: “Back of the envelope” communication and clarifications [16].](image)

### 3.2 Model Based Systems Engineering

To get the system right the first time around, a system engineer has to coordinate between the system’s requirements, the system’s structure, the system’s behaviour, the stakeholders, the timing and the costs among other things. One should wonder if not all engineers are Systems Engi-
neers. A mechanical engineer would not design a gear without also considering the gearbox or engine it fits in. An electrical engineer would not consider an op amp without paying attention to its power supply or the enclosure the printed circuit will be fitted in. A software engineer would not consider a function or a method without considering the passed parameters. An automatic controls engineer needs to model the plant under consideration as well as the major disturbances. So, in a sense, all engineers are systems engineers as long as the systems’ complexity is manageable. Systems Engineering really shows its appeal as the complexity of the system increases since it demands a multidisciplinary set of skills. The complexity is exciting but potentially dangerous requiring rigorous engineering. Processes and tools are necessary to efficiently and effectively handle the life cycle of the system. Processes were referred in the previous section, but what about tools? One potential paradigm is modeling, leading to Model Based Systems Engineering (MBSE). Modelling comes in several different forms, from mathematical equations to drawings (c.f. figure 3). As in any engineering art form, modeling is an essential component. We need to be able to model systems, that is their structure and behaviours while being able to validate the whole system towards the needs of the customer. In software Engineering, one attempt for a modelling “tool” has been the Unified Modelling Language (UML). It was developed during the early 1990’s and later adopted as a standard by the Object Management Group [17]. An extension to UML is SysML to address the modeling of systems. The taxonomy of diagrams in SysML depicted in figure 4.
The idea is to clarify how the system is built up and how it behaves using diagrams. One should be careful not to think of SysML as being just a collection of diagrams. As with UML, there are people who think they are modelling by just drawing diagram, but that is not enough. One aspect that makes SysML attractive is that the collection of diagrams is set up within a structure and the diagrams are inter-linked with each other. The structure is searchable and traceable (i.e., one can review the history of changes). This enables stakeholders to navigate with ease through the system. For example to go down into the details and zoom back out to a bigger picture.

With such tool one can easily cross-reference the systems’ requirements with tests to validate and verify the systems. One can iteratively refine a sub-system and grasp how this influences other parts of the system before it is even built. As a system gets more complex, so does its model components and a good tool is indispensable. This is of great importance in the initial phases of a system design to really understand the need for the system. An illustration of this can be found in Brown’s book on Object Oriented Analysis [19].

A comprehensive set of 170 slides of Systems Engineering and MBSE with tools is available from Linköping University. An introduction book is “A primer for Model-Based System Engineering” by Long and Scott [20]. Another book is the “SysML Distilled: A Brief Guide to the Systems Modeling Language” by Delligatti [18]. One of the major tool supplier is IBM with its Rational Rhapsody family product. IBM has a video showing how
the tool has helped an automotive manufacturer adapt a sub-system to different product lines to be released in different countries [21]. The point being that a good model and tool will allow a system owner to save time and money in the long run.

SysML aims to include an interchangeable format such that the work done with one tool brand could be used by another sub-contractor using another SysML tool. Yet, SysML tools are not that easily accessible and quite expensive. One open source version is PolarSys based on Eclipse [22]. One needs to reflect on the choice of modelling tool as one embarks on such a journey.

3.3 Domain specific meta models

A potential contender to SysML is meta models. We can take specific tool: MetaCase and focus on their automation examples [23].

3.4 Scientific literature

With systems complexities constantly increasing, so does the need for Systems Engineering and likewise do scientific publications around the topics. Using a search engine to find literature with keywords such as Systems Engineering, MBSE, Automation, or Smart Grid, reveal an increasing set of articles.

We can be even more specific and tie them to the IIP gray literature. When it comes to system configuration and IEC 61499, one finds articles on model-driven engineering of manufacturing automation software with a SysML-based approach, and distributed industrial mechatronics systems [24, 25]. From a controls point of view, there is the use of model-based techniques for achieving multi-mode control architectures [26]. As for Big Data devices, there is a reference architecture for mobile SOA [27].

Arrowhead has also an interest in automation for energy (c.f. page 4). Lopes et al. present MBSE for smart grids as a systems of systems using SysML [28]. One interesting aspect of the article considers the economical aspect of Smart Grid solutions.

Having briefly reviewed the state of the art of Systems Engineering, one needs to tie the concepts back to the problems of industrial processes and the relevance of Systems Engineering to them and specifically to intelligent industrial processes.

4 Problems and their industrial relevance

Systems Engineering is becoming an established engineering subject. Tools exist as well as scientific journals (e.g., IEEE Systems Journal), conferences and higher education programs. However, the purpose of this white
paper is to present the relevance of Systems Engineering with to Intelligent Industrial Processes. In the current section, we make that case with reference to a publication modeling an industrial automation unit and a common industrial component. During this discussion, efforts have been placed to relate it to the other published IIP white papers to enhance the LTU context. This association between the white papers precedes the section on collaborations and the potential road-maps to reach the IIP goal.

4.1 General problems

Referring to the introduction section, an industrial process is a system that is made up of components to produce some product from rawer material. Value is added to raw material through the process such that the industry’s business case functions and the industry strives or at least survives. This chain of processes can be referred to as a value chain. How value chain activities are carried out determine costs and affects profits [29]. It is therefore essential to get a good grasp of the need of the industry. With a life cycle view and a modeling paradigm, Systems Engineering can magnify intelligence of an industrial process via developing an understanding of what the customer really needs. The problem being that the need is not always understood or correctly communicated by the customer or the system suppliers.

A complete industrial process is a complex system. It is so complex that one problem becomes the fact that it is not easily understood and optimized. To improve the processes, automatic controllers have been added to the installations. A common issue is that many controllers remain at their default or factory settings and not optimized for the process. To amplify this, the control loops influence each other and need to somehow communicate and to be coordinated. The interaction between controllers might be difficult to grasp and cannot be done consistently all over a plant. Birk tackles this topic in his white paper and mention a hierarchical approach, which requires communication [4].

There is an innate need for communication between all the controllers, sensors and actuators. Wired communication requires planning and maintenance and wireless communication requires security and robustness. With communication of data, the data can be logged to improve understanding of the systems and processes. During the past 15 years, this accumulation of data has exploded. This collection of data in turn creates yet another problem that is associated with Big Data [5, 6].

4.2 Exemplified relevance

Systems Engineering with its life cycle processes and modeling tools can help harmonize the above problems as one aims to reach the IIP goal. To
make the case, we here focus on one component, e.g., an intelligent actuator, and MBSE rather than considering the whole life cycle. The illustrations (figures) are from a scientific publication with a simple industrial process: “Empirical evaluation of SysML through the modeling of an industrial automation unit” by Linhares et al. [30].

The component considered here is a liquid circulation pump. This component is chosen as an example because it is found in all industries. More concretely, one can choose a Grundfos Magna pump as an example [31]. The pump is quite advanced and includes a micro-controller, different sensors with optional communication modules. It can be set to at least the following modes of operation: auto-adapt, proportional pressure, constant pressure or automatic night-time duty. It can be in parallel with other pumps. There can be hundreds of these pumps in a processing plant with other actuators and sensors. Setting each to the right operation modes when operating conditions changes can be hopeless. Luckily, the pump comes with optional communication modules that enables the devices to communicate over a wired network. Request can be made to the devices and information can be communicated. For the pump, this includes pump speed, flow speed, differential pressure, temperature, hours of operation which becomes a lot of data as one keeps track over time of hundreds of devices.

To this complex scene, one should add the idea of component failure within the pump. The component failure will have system impact with different severity to the pump but also in the system. Intelligent industrial processes need to handle these failures and communicate it to the operation supervision.

To monitor the operation of the plant, modern control rooms are setup and connected to the network of the devices such as sensors, actuators and controllers. It does work well to a certain extent. Deviations from the ideal case are challenging giving rise to the need for IIP and Systems Engineering to build a coherent framework. A quick assessment of the list of conceptual problems shows that an industrial process is a complex system that cannot be fathom. There are thousands of sensors and actuators in a processing plant which need to communicate reliably with automatic controllers that have to be optimized for their exact context. The communication must include the control room where decisions can be made and maintenance planned in alignment with IIP goals.

4.2.1 Structure modeling

The IIP white paper “Automatic Control Perspective” presents several attractive solutions [4]. This includes adaptive and learning type control schemes. In its “Research Starting Point” it discusses hierarchical control
loops and models. The advantage stated is that this reduces the numbers of variable each controller has to handle. So small control loops take care of their own process while at a level up another control loop coordinates those at a lower level in the hierarchy. But, how is this hierarchy built or selected? What is the structure of the industrial process? How is the system documented?

For illustration, Linhares considered a small plant shown in figure 5. SysML models the structure, in part, with block definition diagrams as in figure 6. One clearly can understand that the plant consists of a control subsystem, a supervisory subsystem and a physical subsystem. The advantage is to enable different stakeholders to travel up and down the model and unravel the structure. In this case, the desire is to understand better the physical subsystem and see what it consist of, as shown in figure 7. The first block on the left is a liquid pump, with 1 to * instances. In a development phase, a chemical engineer, a mechanical engineer and a purchasing manager can discuss together if a solution meets the system requirements while a controls engineers discuss hierarchical control structure and discuss the robustness of the control strategies. In a maintenance phase, engineers can plan down times or try to understand an unexpected problem. The structure helps HMI engineers design and update the interfaces in the control rooms.

Figure 5: Experimental unit [30].
The experimental unit uses Foundation Fieldbus as the communication network and it allows the implementation of the supervision system. The supervision subsystem is responsible for the execution of the control strategies. It includes all the associated elements, such as the requested service ports connect the services provided and/or requested by a certain block. Figure 5 shows how the equipments interact with the supervision system and presents it on the computer screen. That integrates the supervision and the control levels of the unit.

In order to describe the control flow between the users and the system, the use case diagram is used. Figure 9 shows the case of plant operation. It illustrates the various types of arithmetic equations (parametric diagrams) and others. The relationship between the parameters, relationships among parameters and mathematical functions are described in the parametric diagram illustrated in Fig. 10.

The objective of the Use Case Diagram (UC) is to describe how the system is used. Figure 12 shows the case of plant operation. This diagram is based on the use case diagram, usually a sequence diagram. It identifies the sequence in which the events are executed and the order in which they are dispatched. This diagram shows the elements involved in the dispatch of the events and procedures. The Sequence Diagram (SD) is a graphical representation of the events and procedures that occur in a system. It identifies the sequence in which these events and procedures occur, and the system or between parts of the system it is used.

The Block Definition Diagram (BDD) describes the structure of the system or of a subsystem by using the Block Definition Diagram. The Internal Block Diagram (IBD) describes the internal structure of the system or of a subsystem. The Block Definition Diagram (BDD) is used to describe how the system is used. Figure 7 shows the case of plant operation. This diagram is based on the use case diagram, usually a sequence diagram. It identifies the sequence in which the events and procedures occur, and the system or between parts of the system it is used.

Figure 6: Block definition diagrams of the system structure [30].

Figure 7: Block definition diagrams of a physical substructure [30].
4.2.2 Behavior modeling

But structure is not sufficient on its own to explain how a system behaves. A physiotherapist does not usually pretend to be a psycho-therapist; behavior of a system needs to also be modeled. To address this problem SysML, and UML for that fact, also models behavior. Figure 4 shows four types of behavior diagram. Figure 8 shows the activity diagram for a use case. It is reminiscent of a traditional flowchart and clarifies interfaces, i.e., inputs and outputs. Clarifications of interfaces, whether mechanical, electronic or software, help in the introduction of new components in re-designs and maintenance of a system through its life cycle.

Intelligent Industrial Processes require to have components that are themselves intelligent. Smart controllers are not the only components in the infrastructure of an industrial process. This necessitates paradigm shifts from many stakeholders. For example, the components must become active members of the system. This begins with a self introduction according to a protocol (e.g., a handshake or a hug depending on the culture). Such behavior can be seen in the white paper “Big Data Devices” referring to Service Oriented Architecture (SOA) [6]. “Devices must therefore be able to announce their presence and capabilities without breaking backwards compatibility with legacy systems and also to be able to be upgraded with new and improved functionality”.

![Figure 8: Activity diagram of the control system [30].](image)

Let us consider again the pump element. It can pump a liquid in different control modes. It can measure and transmit information of temperature and pressure among other parameters. All these are services the pump can offer the system where it is introduced or installed. The pump has to be
active, i.e. communicate and present itself to the system. On the other hand, the system must *somehow* know what to do with the offered services. These services might change when changing the pump or upgrading its embedded software.

SOA as well as automatic controls require dependable communication. The communication can be separated into media and protocol. For a long time wired communication was the standard but wireless communication has made a huge field penetration. The wired communication can be peer to peer requiring many connections and ports or a network with a common communication protocol. Wireless communication does not require detailed planning as wired communication and allow much more flexibilities. They have considerably penetrated the industries with ZigBee, IEEE 802.15.4, WirelessHART and ISA SP100. They have also their challenges and vulnerabilities such as interference and an increased need for security.

With any communication form, the information must be reliable in time and in content. Systems Engineering and more specifically MBSE supports this when it considers the structure and behaviour. For example,
how should a pump equipped with a wireless communication module and SOA behave in an industrial setting? How does system make sure that the information is not corrupted and comes from the correct pump on the correct hydraulic circuit?

To elucidate the idea, we can consider the start up sequence of a mobile phone. As the phone is turned on, it communicates with the SIM (Subscriber Identity Module) card. It then asks the user to identify himself with a PIN (Personal Identification Number) code. The phone then can obtain the international mobile subscriber identity and the related key is used to identify and authenticate itself as a subsystem within the telecommunications system. The sequence of communication and information used in the communication is of interest to many of the stakeholders. It must be communicated clearly as with a sequence diagram, e.g., as in figure 9.

An interesting set of sequence diagrams would be about the installation, configuration and firmware upgrade of a pump with SOA within an industrial process. How does the system and the pump make sure that the pump is in the correct hydraulic circuit? How does the pump offer its services to the system? How does the pump get information for its configuration, e.g., type of control mode it should enter or the control parameters it should use? How does the pump remotely gets a firmware upgrade? How does the pump make sure that the firmware upgrade is not a malicious virus?

Another set of behaviour diagrams are the State Diagrams, e.g., start-up, operation, re-programing, stand-by states. Figure 10 shows the states of the experimental plant.

Another set of behaviour diagrams are the Use Case Diagrams. They usually consider how should or could humans interact with the system. Figure 11 shows how different actors interact with the system at a higher level. Within an industrial process, being clear and communicating roles and responsibilities promotes harmony. Adding intelligent components that handles disturbances does not dismiss that requirement. There is usually an intended use of a component and many ways to use the component in non-traditional ways. Use case diagrams consider a limited set of cases to consider potential situations.

As one considers different use cases, there is also a need to consider different scenarios. In the white paper Enabling research challenges by Dependable Communication and Computation, there is a discussion on reconfiguration. When necessary, an intelligent industrial process needs to be able to adapt and reconfigure itself. It should be noted that this is different from failure detection when a low level component fails. The requirements for the systems or industrial processes must also address component failures and graceful degradations. Birk also writes about a general setup.
Figure 10: Operation state machine [30].
for an active fault tolerant control system. To address this, industry uses failure mode and effect analysis (FMEA) and its relatives known as Functional, Design, or Process FMEA. FMEA is a tedious exercise in which one considers the failure mode of each component of a subsystem, its effect on the system and considers the detection of the failure. This enables a ranking of critical impact of failures on the system.

4.2.3 Validation & verification

When it comes to system requirements, there needs to be validation and verification of the design to ensure that the requirements are met. When the requirements are written in a text document, it is easy to overlook some of them. This gets even worse when there are multiple versions of the requirements. Identifying them is an ID number and placing each requirement in a database can help. In SysML, requirements are part of the model and can be linked to the relevant component and behaviors.

The purpose of documentation is to facilitate communication as well as record designs and decisions. In regular operation and maintenance, the documentation helps understand problems as they occur or plan to deal with potential problems. In its inherent form, Model Based Systems Engi-
Figure 12: Systems requirements in SysML [30].
Engineering naturally contributes to useful documentation and traceability. An intelligent element within a system should add value. But to achieve the maximum added value to the value chain, the complete system or process must be understood. Models, whether mathematical, reduced, or drawing help the understanding the system or process in our present case. Systems Engineering is a multidisciplinary area that can help IIP towards its goal. We can therefore wonder how this multidisciplinary collaboration can be implemented by IIP at LTU.

5 Potential collaborations

Systems engineering being an interdisciplinary field of engineering, collaboration is essential. In this document, collaboration is divided into three parts: internal to LTU, external to LTU as well as the available interfaces.

5.1 Internal collaborations

The most obvious place to start with collaboration is with the areas of engineering that have already published white papers for IIP [4, 5, 6, 7]. They have already shown their interest in the topic and can contribute strategically with their skills and experiences.

At the department of Computer Science, Electrical and Space Engineering there are other divisions that can contribute. One example is the research of Information Systems with its ties to Context Specific Meta Models (c.f. section 3.3).

At the department of Engineering Sciences and Mathematics, the division of Product and Production Development has experience with life cycle management. One tool that they use is Siemens’s Teamenter, which is a suite of Product Lifecycle Management (PLM) applications including support for requirement management, electronics hardware as well as multiphysics simulation including control systems.

Naturally, there is the division of Operation and Maintenance Engineering at the department of Civil, Environmental and Natural Resources Engineering. If an industrial process has to be efficient and effective, operation and maintenance are an integral part of the system. There is a fundamental issue with too much internal cooperation as discussed in the SWOT analysis (c.f. section 6.1). This problem has to do with research funding bodies whose aim is also to develop national and international cooperation. One potential work around is that an internal research area uses its network to set up an external collaboration as a sign of good will.
5.2 Internal-external interfaces

LTU does have interfaces between internal research and external ones as well as industry.
When it comes to process industry, LTU’s natural interface is ProcessIT Innovations. It has successfully facilitated cooperation between research and industry several times. It has even extended itself to Europe with ProcessIT.eu, its road map and its projects.
LTU has other interfaces to industries that have stakes in process industries as component suppliers. One example is SKF-LTU University Technology Center aiming to develop advanced condition monitoring smart bearings.

5.3 External collaborations

Having interfaces to industry, it is clear that there are process industry stakeholders interested in LTU and IIP. One can just turn to ProcessIT Innovations’ homepage and look at the impressive list of projects they have coordinated. Under each project, one can find the partners involved.
Looking at the partners in a project like Arrowhead, one comes up with an impressive list of stakeholders.
Finding potential industrial partners in research project is therefore possible. With the clear goal stated for IIP, the question becomes: what is the strategy developed to reach it? What are the mileposts along the road to the objective? Systems Engineering can help define this roadmap.

6 Road-map for LTU research

The general goal of IIP is quite clear: for an industrial process to produce as much as possible with the least resources. The intelligent part has to handle deviations in the resources and processes to continuously achieve the goal. The goals of the individual stakeholders may vary from that goal.
For example, for a pump manufacturer, the goal is to sell as many pumps as possible at the lowest production cost. However, aligning the stakeholders’ goals with each other leads to long term profits if and only if the short and long term benefits are clear.
The challenge is this section is to develop a strategy to reach these multiple goals and align them together with the help of Systems Engineering.
More specifically to the white paper, how should IIP and LTU act to lead these strategies. We therefore present at a brief SWOT analysis and propose three coincident road maps.
6.1 SWOT analysis

To invest in a mission or project, one must assess the risks and opportunities with any endeavour to achieve the objective. We review here a SWOT matrix with internal factors as the strengths and weaknesses and external factors as the opportunities and threats.

6.1.1 Strengths

There is quite a collection of strengths for IIP at LTU. There are several research subjects and division that can contribute directly to the development of improved components. There are research centres like ProcessIT Innovations that ties or connects research and industries. At the university level, there are the recognised area of excellence such as Intelligent Industrial Processes and Future mining. So, internally, LTU has all the assets to succeed in contributing to the goal of Intelligent Industrial Processes.

6.1.2 Weaknesses

From the point of the current white paper, the major weakness that LTU has is a lack of System Engineering research and education. We do see some traces of it as research in Product Lifecycle Management, e.g., Teamcenter, at the Computer Aided Design division. There is also research at the Information System division or at the division of Dependable Communication and Computation Systems.

It is of interest to see how IIP will plan and actually address this weakness and its impact on the university.

6.1.3 Opportunities

The opportunities for IIP are great and multiple. There is a regional as well as an international need from industrial processes. There is an interest from national funding bodies as well as European ones. There are additionally interests from ProcessIT.eu and Arrowhead.

6.1.4 Threats

The external threats are mainly the funding of research for IIP, specifically in this case, funding Systems Engineering. Being a multi-disciplinary area, it can become unclear to unfamiliar reviewers if the research is necessary. Another threat is the aspect of the funding bodies that promotes cooperation between different actors. For example, the European Union requires actors from different countries and within them different fields, e.g., industry and academy. As stated earlier, if one’s network is internal to the university, it would require an internal support to freely make the connection.
6.2 Three road maps

The university’s structure rests on three pillars: education, research and cooperation with industry. Intertwining those three pillars alludes usually to a triple helix that aims to an upward spiral of mutually beneficial cooperation. Presented are three road maps towards the overall goal of IIP and yet tuned towards the specific goal of the stakeholder or pillar in this case. The three road maps are not exclusive and can be concurrent, sequential or overlapping in time. Their origin of funding reveal in part their distinctions.

6.2.1 Education

In education, the goal is to promote “functional” graduates. That is, new graduating students should be able to function within industry right away without requiring further education. Beyond their specialisation (e.g., electronic hardware, automatic controls, etc.), LTU graduates should be team players and contributors to the employing organisation. Sheard describes twelve Systems Engineering roles [32]. They include requirements owner, system designer, system analyst, validation/verification engineer, logistics/ops engineer, glue among subsystems, customer interface, technical manager, information manager, process engineer, coordinator, classified ads SE. The question is how does an education prepare the students to complementing team members.

To prepare students to be team players and contributors, project courses have been setup in their education. Some education programs have more projects than others resulting in different levels of readiness. Cooperation with industry, in this case, it should be the Industrial Processes. One example in 2014 is the cooling of pellets in the steel processing with LKAB. The students had to consider the life cycle of the cooling system, brainstorm about different solutions and refine down to a single solution, which they implemented. The benefit of Systems Engineering in project courses is to allow students with different backgrounds to work in teams and understand the needs, their own contributions and their interactions.

An educational road map to promotes Intelligent Industrial Processes leads future engineers to assemble real industrial systems with Systems Engineering knowledge and tool experience. This can be done in project courses during which the students work with a small sub-system defining its requirements, structure and behaviour while documenting the sub-system with consideration to its complete life cycle.

In Sweden, the state funds education. The funding is therefore tied to the presence and performance of students. Simple projects, with limited budgets, can be imagined by the faculty and implemented by students. The results remain at a theoretical state. An industry can enliven the project
with a real need, expertise and funds, such that an industrial partner is always desired in project courses.

6.2.2 Research

The goal in research is to “discover” something new that can be published while it is still fresh. In the case of IIP, the research tends to be applied research, which directly or indirectly relates to its usability in industrial processes. Systems Engineering, being multidisciplinary, requires cooperation between different groups with the participation of industry to add a touch of reality.

A research road map should connect EICT, Industrial Electronics, Operation and Maintenance divisions with the Signals and Systems division to build a systematic framework in which one can place blocks commonly found in industrial processes. We can return to the pump example discussed earlier. Can Industrial Electronics develop a communication module for the Magma pump with a secured service oriented architecture? What are the sequence diagrams for installation, measurements, maintenance, upgrades and retirement of the pump? How does EICT deal with scalability and security of (Big Data) information from several pumps in a growing industrial process? How does the control setting are altered online in the case of a system reconfiguration? Funding for multidisciplinary research on its own is not easily attainable. It is much easier to find financial bodies that require co-financing from industrial partners. This moves the issue right away to a cooperation with industrial stakeholders.

6.2.3 Industrial cooperation

A road map where research is driven by an industrial need is quite a simple one. Through ProcessIT Innovation or Arrowhead, for example, industrial stakeholders grasp that the expertise at the university can be beneficial to its process. Together, researchers and engineers formulate and answer relevant research questions. Upon agreements, these results can partially be published and knowledge transferred to students in classrooms. There are several examples at the university where this has been the case. A large current example is the SKF-LTU University Technology Centre in advanced condition monitoring. They sponsor almost 10 Ph.D. students and their associated senior researchers.

The difficulty with this road map is the discovery of the IIP expertise as seen from outside the university. Networking is the obvious solution, followed by centres like ProcessIT Innovations or the areas of excellence. One can try to rely on publications or productification of research results that might attract attention.
7 Conclusion

It is self-evident that Intelligent Industrial Processes can only reach its goal by adding intelligent components and services within its systems. It is also clear that industrial processes are not naturally occurring systems but are engineered. To engineer them well, IIP must rely on Systems Engineering as a keystone along with the traditional engineering research.

In its introduction, the NASA Systems Engineering Processes and Requirements document states: “Systems engineering at NASA requires the application of a systematic, disciplined engineering approach that is quantifiable, recursive, iterative, and repeatable for the development, operation, maintenance, and disposal of systems integrated into a whole throughout the life cycle of a project or program. The emphasis of systems engineering is on safely achieving stakeholder functional, physical, and operational performance requirements in the intended use environments over the systems planned life within cost and schedule constraints” [33]. Replacing the name NASA in the quote text with an industrial process name leads to a text that meets IIP’s goals.

References


