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Research Article

Integrative Approach to the Plant Commissioning Process

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Commissioning is essential in plant-modification projects, yet tends to be ad hoc. The issue is not so much ignorance as lack of systematic approaches. This paper presents a structured model wherein commissioning is systematically integrated with risk management, project management, and production engineering. Three strategies for commissioning emerge, identified as direct, advanced, and parallel. Direct commissioning is the traditional approach of stopping the plant to insert the new unit. Advanced commissioning is the commissioning of the new unit prior to installation. Parallel commissioning is the commissioning of the new unit in its operating position, while the old unit is still operational. Results are reported for two plant case studies, showing that advanced and parallel commissioning can significantly reduce risk. The model presents a novel and more structured way of thinking about commissioning, allowing for a more critical examination of how to approach a particular project.

1. Introduction

1.1. Background. Plant modifications are an ongoing process throughout the life of any process plant. Reasons for modification include efforts to improve reliability, production capacity, quality, or productivity. Seamless incorporation is the key concern associated with the installation of any new equipment in an operating plant due to the high cost of process downtime. Several steps can be taken to minimise the risk associated with the installation of new equipment such as hazard and operability studies, project management, development of redundancy plans, and commissioning of the new equipment.

Of these, commissioning is an essential activity in many plant-modification projects and has significant implications for project success. Yet paradoxically it tends to be approached in an ad hoc manner. It is often included in project plans, so it is not that people are ignorant of commissioning. Rather, the problem is that there is a lack of systematic approaches to commissioning, so it is frequently left to tradespeople and plant operators to manage in whatever way they see fit. This is an undesirable situation since it results in unpredictable outcomes. In some cases it can even cause serious problems. An extreme example would be the catastrophic failure of the Chernobyl nuclear power plant (1986), which was caused by operators attempting an ad hoc test of the efficacy of a modified emergency cooling system.

This paper presents a structured conceptual model for the commissioning process, and two cases studies showing application to operating plant.

2. Existing Models of Commissioning

2.1. Literature. Many authors have highlighted the value of commissioning from a range of different perspectives but they all agree that commissioning and the integration of a new project is critical to the success of any project [1–10]. However commissioning is poorly defined and is interpreted ambiguously [6, 11], which leads to inefficient utilisation within industry. In this paper "commissioning" is defined as the disciplined activity involving careful testing, calibration, and proving of all systems, software, and networks within the project boundary [5].

2.2. Current Models of Commissioning. Factors that are known to affect the commissioning process include the following.

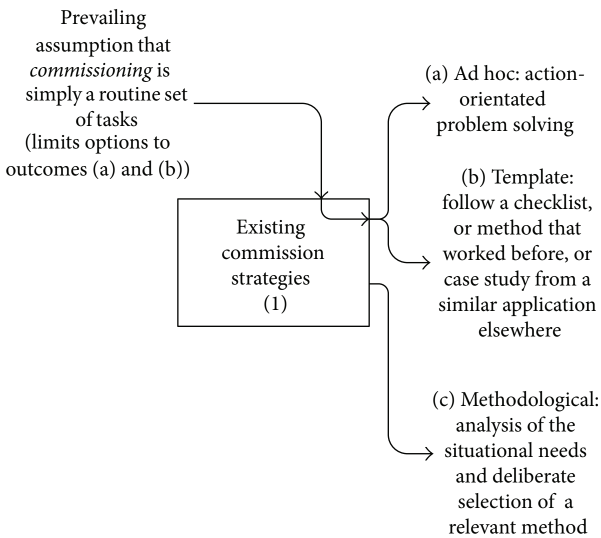

FIGURE 1: Three common strategies for commissioning, broadly reflecting the approaches described in the literature. If commissioning is perceived to be simply a routine set of tasks, which is a common assumption, then this tends to preclude any more thoughtful approach to the problem.

(i) Type of project. Thus situational variables are important; that is, the factors that resulted in a successful (or failed) commissioning outcome in one case are not necessarily transferrable to a different situation.

(ii) Who is in charge of the phase. Commissioning can be completed by a range of different groups depending on the project. It can be the equipment manufacturers, operation team, or a separate commissioning team depending on scale and requirements of the project [12]. The relationships between these people are also important (social dimension) [6, 13], hence also contractual obligations (see (iv) below).

(iii) Number/type of phases. Commissioning can also be broken down in several sections such as planning, precommissioning, testing, integration, monitoring, documenting, and handover depending on the level of complexity of the project. This requires careful project planning (see (iv) below).

(iv) Project planning and contractual sufficiency. It is widely recognised in the literature that commissioning requires deliberate planning, as opposed to ad hoc treatment. Thus it needs appropriate consideration in the work breakdown structure and project planning [14], allocation of resources, transferral of those costs into the initial contract [9, 15–18], and creation of specific operating procedures (especially important for safety-critical plant like boilers [19]). This corresponds to the "integration" tasks in the project management approach [6].

The commissioning process has been examined for a wide range of different projects [2–5, 8, 20, 21]. The predominate approach can be described as task specific; the literature tends to identify specific tasks that should be completed as part of commissioning. Thus the focus has been on completing multiple checks on a system to ensure it will operate as expected. Thus there are many reports in the literature, too numerous to mention, about commissioning *experiences* in specific case studies. These are undoubtedly helpful, especially for lessons learned and application to comparable situations. They are also systematic, in a way, especially in the provision of templates and checklists to guide practitioners.

However there is a lack of holistic or integrative models. There is much less literature at the next higher level of abstraction, which is the commissioning process in general. At this level we are interested not so much in case-specific experiences but in the fundamental principles and the methodology. What exists at this level is primarily in the area of instrumentation and control; some examples are [5, 22, 23].

Thus the existing commissioning strategies in the literature can be categorised into three types, see Figure 1. These are (a) ad hoc, which is action-orientated problem solving; and (b) template, which involves using a checklist, or operating procedure that worked before or in another situation. Both (a) and (b) are premised on the assumption that commissioning is a routine set of tasks. The third strategy challenges that premise and calls for a deliberately thoughtful approach. Thus the third category in the literature is (c) methodological, which involves analysis of the situational needs and deliberate selection of the most relevant of several possible commissioning methods.

2.3. Issues and Problem Areas. A clear refrain in the literature is that commissioning (i) needs deliberate project management, but (ii) is too often not given the attention it deserves. One of the issues with commissioning, which contributes to problem (ii), is that the value thereof is hard to quantify. Justifying the value of commissioning may be completed using qualitative analysis similar to quantification of risk in a project [24]. This is based on the consequence and probability of the system failing to operate as anticipated. In other cases there is no attempt at justification at all, so the value is not appreciated.

Another issue is the tendency to underresource the commissioning in the project planning, which is issue (i) above. Underresourcing is due to several factors such as its omission in the project management. There is often a high level of variability as a result of the case-specific nature making it difficult to fit into the established planning structure. Existing project management frameworks, such as the PMBOK [9], are general approaches. While they acknowledge the commissioning stage they do not, and cannot reasonably be expected to, provide case-specific guidance on commissioning. They treat commissioning very lightly and rely on the practitioner to identify whether or not commissioning is an important part of the project. The literature suggests that practitioners too often fail to realise the importance and therefore fail to plan sufficiently. Alternatively, project managers may simply be overly optimistic about the risks associated with the installation of a new system. Whatever the reason, the result can be insufficient resources being allocated, with the consequence of poor completion. Incorporation of a broad conceptual model of commissioning into the project management practices would be the first logical step. Commissioning draws from several project knowledge areas such as integration, communication, and risk management. The logical approach is to incorporate into the project life cycle between the execution and closing phases [4, 6, 8].

2.4. Problem Definition. Current models of commissioning tend to be simplistic, and relevant only to specific areas. They are focused on the process and consequently tend to produce a somewhat prescriptive list of tasks that need to be performed. A higher-level reconceptualisation of the commissioning process, with the development of a more general theory, could be valuable.

The purpose of this work is to develop a more holistic and integrative theory of commissioning. The specific emphasis is on reducing process downtime, without compromising plant reliability. This is worth attempting as it has the potential to provide a general framework in which the other more process-specific models can be placed.

3. Approach

We start by reconceptualising commissioning in broad terms. We categorise the commissioning strategies according to the operational risk. This results in three categories: direct, parallel, and advanced. We then apply a system modelling method to embed these within the broader manufacturing context. Finally we apply the new framework to two case studies to demonstrate the applicability.

4. Results

4.1. Categorisation of Commissioning Projects

4.1.1. Starting Premise. We start with the premise that the value of commissioning is essentially one of systematic risk reduction, that is, used to minimise the risk associated with the installation of a new piece of equipment. More specifically the application of commissioning for the installation of new equipment into the process industry reduces the risk of equipment damage, environmental health and safety, and process downtime.

Thus commissioning is a strategy for treating risk [24]. This has the further important implication that the treatment, hence type of commissioning, can be aligned with the degree of technical risk that the organisation can accept. Thus we specifically link commissioning, as a treatment strategy, to the concept of "tolerable risk" within the risk management literature, and to the concept of strategic risk for the organisation as a whole [25]. This also has contractual implications in project-setup phase, where there is a need to differentiate between the commissioning risk elements and proportion them between the equipment manufacturer, project management organisation, and plant owner [26].

From this starting assumption we identify three categories of commissioning, as strategies in response to organisational risk-tolerance. These are direct commissioning, advanced commissioning, and parallel commissioning. Each has strengths and weaknesses. They can be deployed individually or together.

4.1.2. Direct Commissioning. Direct commissioning is the classical approach to commissioning where the new equipment is installed and the system must remain offline as commissioning is completed. Direct commissioning is the most straightforward approach as no additional equipment or simulation is required. The new equipment is installed into its operational position and the process cannot restart until the system has been commissioned and is running correctly. There is a high level of downtime in this process as the whole system cannot be operated until the new unit is electrically, mechanically, and operationally tested. There is also the risk of having to reinstall the old unit if there are significant complications at any phase of the commissioning process. Direct commissioning is often reserved for well-established unit operations such as new pumps and flow meters. Direct commissioning is most effective when it is used on well-established system and ones that are not a key requirement of the process.

4.1.3. Advanced Commissioning. Advanced commissioning is the process of operating the new unit in advance of installation and in isolation of the main process operation. Advanced commissioning requires the simulation of all proprietary systems that interact with the new unit. Simulation can be extremely complicated or simple depending on the level of interaction between the process and the new unit. (In this context "simulation" can refer to the artificial provision of physical inputs to the new machine or unit, smaller scale models, and mathematical modelling of the functional behaviour of the unit.) Advanced commissioning allows for the electrical, mechanical, and part of the operational testing to be completed. The full functionality of the unit cannot be proven as the system is being simulated by external means, which will always be an approximation of reality. Advanced process is extremely valuable for the development of new technology as it allows for the verification of novel processes at low risk. The most common type of advanced commissioning is the development of model systems which both simulate the operation of the system and the new unit. Advanced commissioning can also include computer simulation of new process which provides a cost effective method of developing concepts in the early stages of design. Advanced commissioning is valuable at proving conceptual designs of new technology. The main drawback of advanced commissioning is that the process is only simulated so there is still the potential that the unit can fail when installed into its operational environment.

4.1.4. Parallel Commissioning. Parallel commissioning is the testing of the new system in parallel to the operating system. Parallel commissioning is the most rigorous form of physical and operational commissioning. It allows for the new unit to be tested under full operational conditions, with low risk of significant process interruptions due to the added redundancy of the old system present in an operational capacity. However it also has the highest cost as it requires the duplicate hardware systems and additional structural space. The only risk associated with parallel commissioning is the integration between the two systems. Often there is some type of switching or merging component in these systems which may require minor process stoppage for installation. Parallel commissioning is often completed when it is critical that the process must not stop for any extended period of time. It often lends itself to processes with few interactions between new unit operation and the rest of the process. Parallel commissioning is seldom utilised due to the requirement of a process that can accommodate both the new and old unit.

4.2. Conceptual Model. Having identified three types of commissioning, we next seek to set those within a conceptual framework. This is worth doing as it has the potential to identify the situational variables relevant to each type of commissioning. This in turn can be used to further build a theoretical foundation, and provide guidance to practitioners.

4.2.1. Approach. The modelling method uses a structured, deductive process to decompose the process being analysed into multiple subactivities (functions) and for each deduce the initiating events, the controls that determine the extent of the outputs, the inputs required, the process mechanisms that are presumed to support the action, and the outputs. The model was then inductively reconciled with elements of the existing body of knowledge on this topic, and successively refined. The end result is a graphical model that describes the relationships between variables, thereby providing a synthesis of what is known and surmised about the topic. The model is expressed as a series of flowcharts using the integration definition zero (IDEF0) notation [27, 28]. With IDEF0 the object types are inputs, controls, outputs, and mechanisms (ICOM) and are distinguished by placement relative to the box, with inputs always entering on the left, controls above, outputs on the right, and mechanisms below.

4.2.2. Develop Production Capability (Prd-1). The broader context is that commissioning occurs as part of the development of production capability, and our model starts at this level. (This is already the second level into the model; the top level, which is not shown here, includes product design, operation of the plant, control of production flow, quality, distribution to market, packaging, health and safety, lean/JIT, among other activities. However the present paper focuses on the commissioning activities.) See Figure 2. Commissioning is included as element 5 and occurs towards the end of the plant-development process. Other important activities are the following.

(i) Determine manufacturing/production sequence.

(ii) Design of the production plant, which also includes the plant layout, material handling, plant control and automation, and (for manufacturing) the development of production tooling and flow control, for example, just-in-time (JIT). Analysis of technology risk (9) is another activity associated with the design phase.

(iii) Building the production system (4), and the associated project management activities.

(iv) Decommissioning the plant (7).

(v) Project management (8). We note the importance of project management methods in supporting many of the activities of commissioning. There are several models of project management that might be inserted here, including [9, 29], but these are not specific to commissioning and therefore not detailed further at this point.

We do not deal with these other activities here, but instead move the focus to the test and commission activities. Before doing so, we draw attention to some hollow arrows, which represent errors, in particular design and construction errors, at (2) and (4), respectively, and the possibility for unintended plant behaviours at (5): low productivity, safety issues, staff usability problems, product quality defects, and so forth. This point is important because the commissioning model that follows specifically seeks to address these risks.

4.2.3. Test and Commission Production System (Prd-1-5). The model for commissioning a new piece of plant equipment is shown in Figure 3 (Prd-1-5). The conventional commissioning process is included here, as are the new concepts for commissioning approach. One of the conventional activities is to verify instrumentation and control systems (1), which involves the systematic checking of installed hardware against plant schematics. The checks are progressively done for connectivity, cold operation, hot operation, and process control. We do not detail those processes here and instead refer the reader to source material [5] which has information that is useful to practitioners. The final objective of commissioning

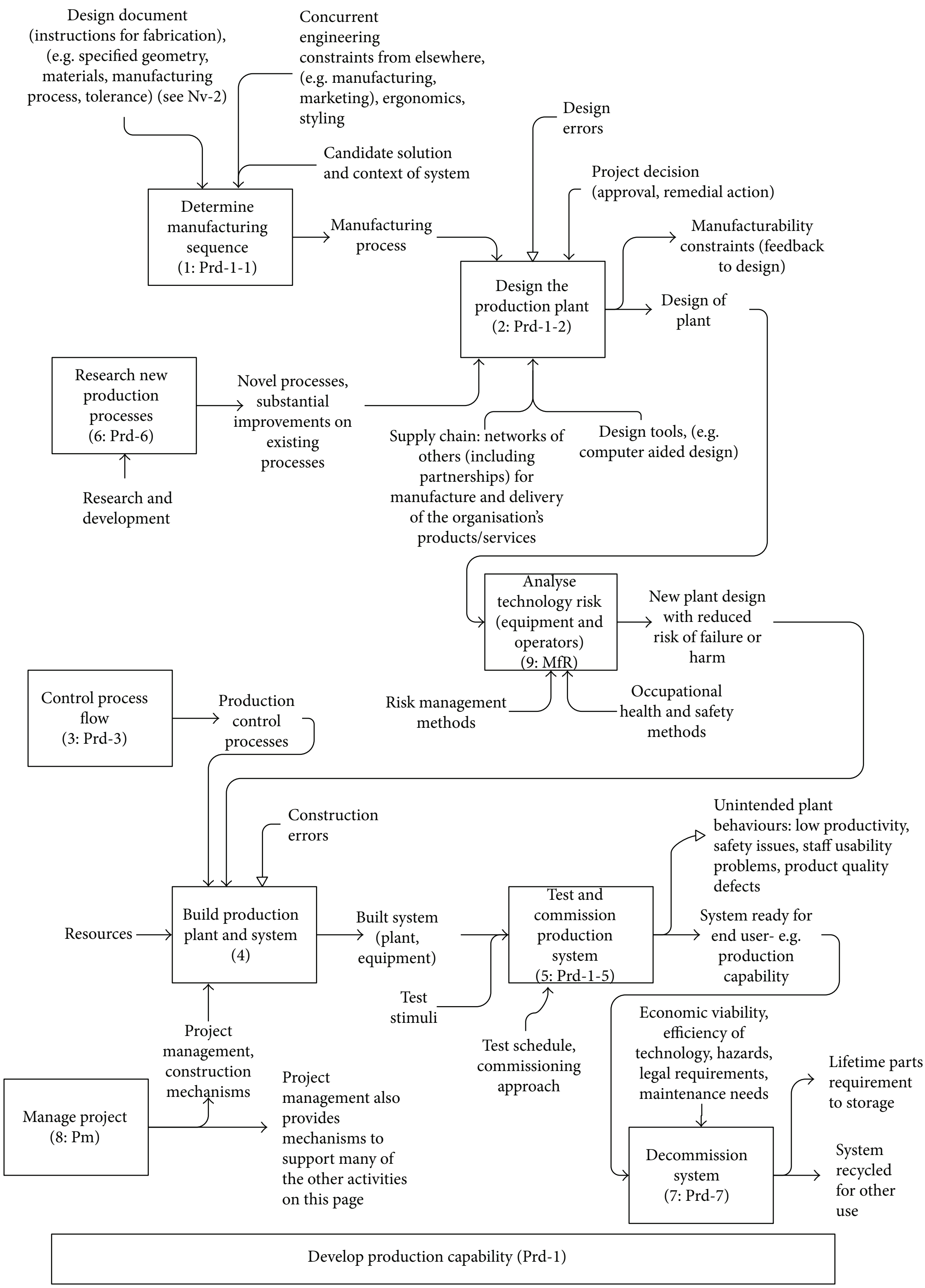

Figure 2: Model for the development of production capability.

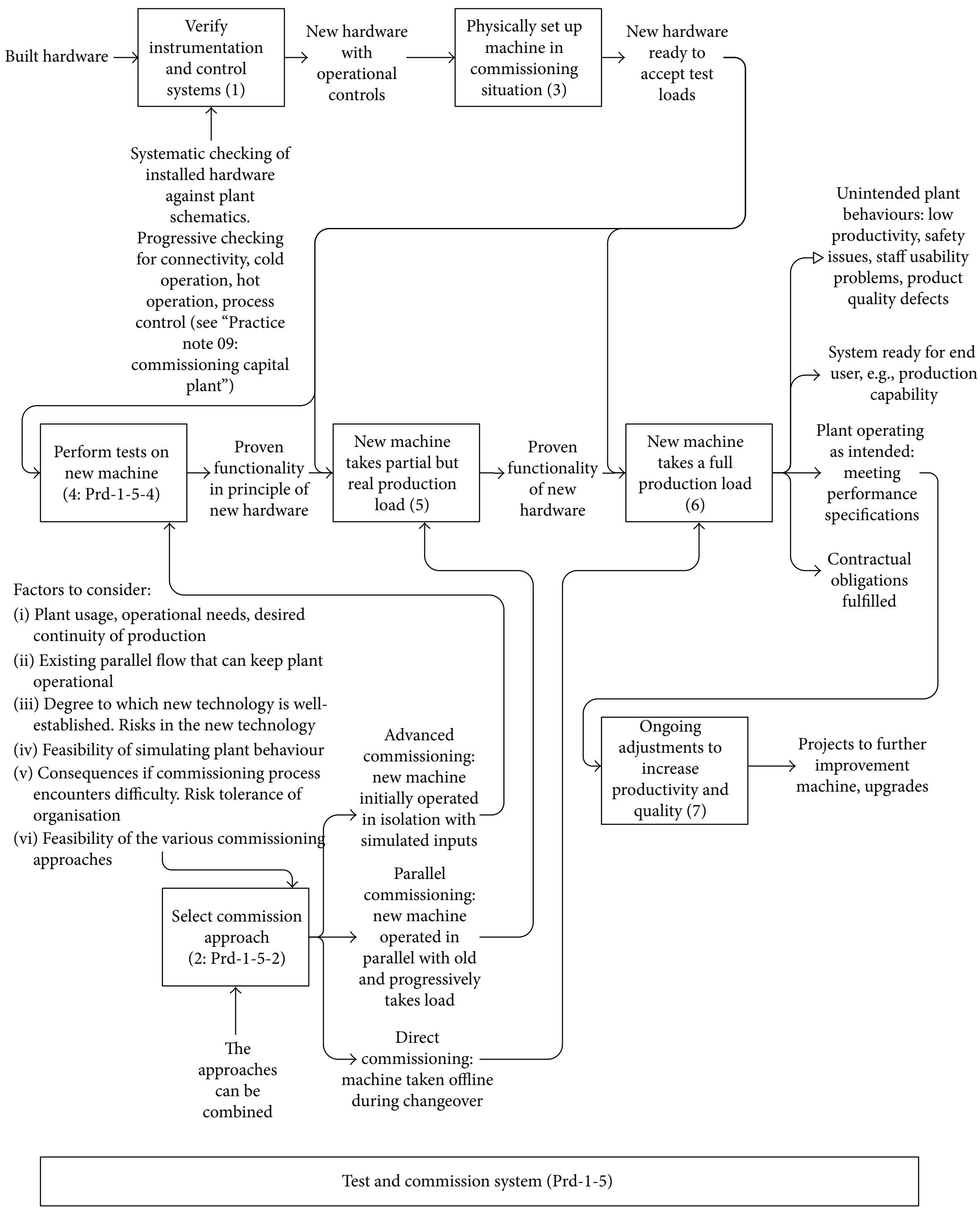

Figure 3: Model for the test and commissioning activities.

is also well known, to deliver an operational production system (6) that is ready for the client to use.

Where our model differs is the inclusion of a deliberate stage of deciding which of three commissioning approaches to use in the situation (2): direct, advanced, or parallel. We also note in passing that the quality and lean imperative for continuous improvement will generally mean that there will be ongoing adjustments to increase productivity and quality (7) after the machine has been commissioned. Thus commissioning the machine and closing the contract with the client may be the end of the involvement of the machine builders, but are not the end of the life cycle for the machine itself. This again has contractual implications in the form of service and warranty support from the vendors, and

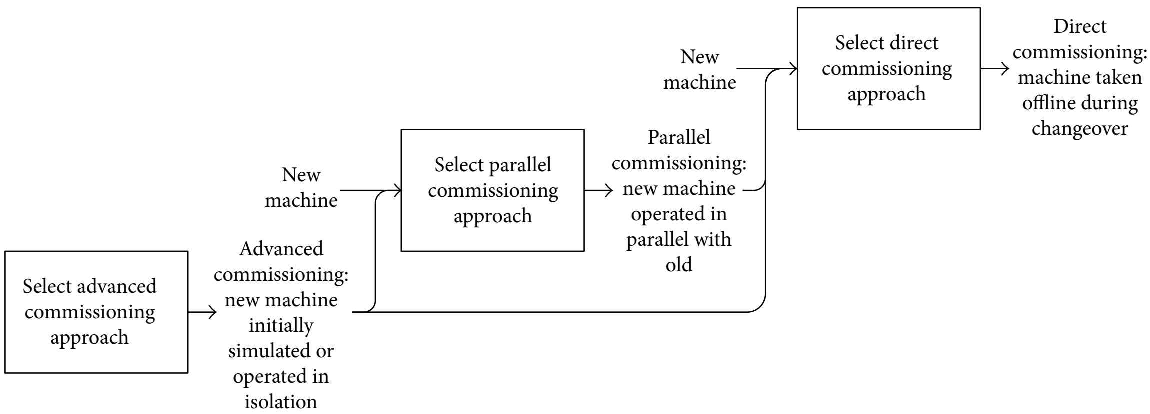

Figure 4: Relationship between the three commissioning approaches: advanced, parallel, and direct.

reliability centred maintenance by the plant operators. There is also the decommissioning to consider, which can be a project in itself. (In extreme cases, e.g., nuclear power plant, the cost of decommissioning is comparable to the initial construction cost. If there has been a catastrophic failure of the plant then the decommissioning cost can vastly exceed the construction cost.)

4.2.4. Select Commission Approach (Prd-1-5-2). The decision involves a choice of direct, advanced, or parallel commissioning. These are not mutually exclusive. Instead some of them may be done sequentially, as shown in Figure 4. For example, advanced commission may precede either of the other two.

The various factors relevant to this commissioning decision are anticipated and clustered in groups: ability to recover from a failed installation, assessed or perceived technology risk, desired operational continuity, and timing considerations. The detailed model and the factors within each cluster are shown in Figure 5. At this stage the model is primarily logical and qualitative and is intended as a debiasing tool and a guide to action rather than a decision algorithm. It is also a framework for further research in that it proposes subjective relationships of causality that can subsequently be tested and developed as appropriate. (It may even be that in certain areas it could be possible to develop a mathematical model to support the decision, particularly in well-defined areas. Specifically, the model incorporates risk assessment and it is not impossible that there could be well-defined situations where the variables can be determined with sufficient precision that a quantitative risk assessment coupled with (say) a Boolean consideration of the other factors might make for a sufficient mathematical model. However further research would be required to take it to this level of detail.)

Thus the model proposes that the following decision factors are relevant.

(i) *Advanced* commissioning is appropriate where technology risk is high, operational continuity is required, and timing constraints are tight.

(ii) *Parallel* commissioning is appropriate where operational continuity is required and timing constraints are tight.

(iii) *Direct* commissioning is appropriate where technology risk is low, operational continuity can be disrupted, and timing constraints are loose.

Finally, to complete this part of the conceptual framework, a model is provided for the testing activities of commissioning; see Figure 6.

5. Case Studies

Two cases studies were completed to determine the relevance of this commissioning model in the process industry. First was the development of a novel vertical screw system in the fertilizer industry which used the advanced approach to commissioning. Second was the installation of a ship unloader in the aluminium industry which used a parallel approach to commissioning.

5.1. Vertical Screw Project. Ballance Agri-Nutrients single superphosphate plant at Awarua (New Zealand) had recently designed and installed a new phosphate rock feed system. A new vertical screw system was developed to replace the old gravity feed vertical chute which was prone to blockages in the highly reactive and humid environment present in the reaction chamber. The vertical screw was designed to increase the reliability of the process by forcing the rock into the reaction chamber, hence reducing the number of blockages. An *advanced* approach to commissioning was completed for this new project due to the risk associated with the installation of a complex and untested unit into a critical position in the production line.

The advanced approach to commissioning allowed for rigorous testing to be completed in a controlled environment with low risk to production capacity. Commissioning was completed in two stages with the development of a model system and full scale commissioning of the new system before installation.

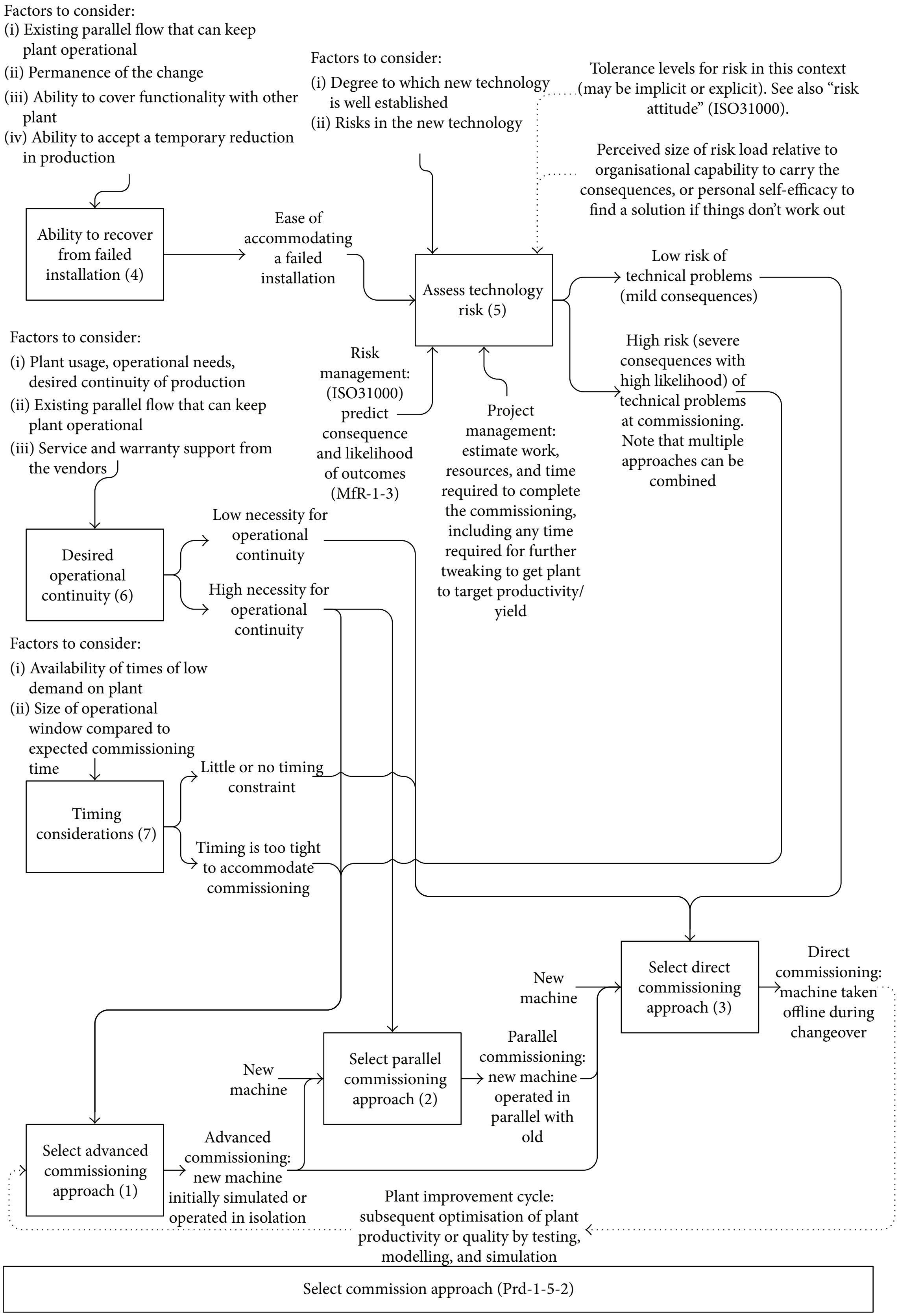

FIGURE 5: Factors relevant to the commissioning decision.

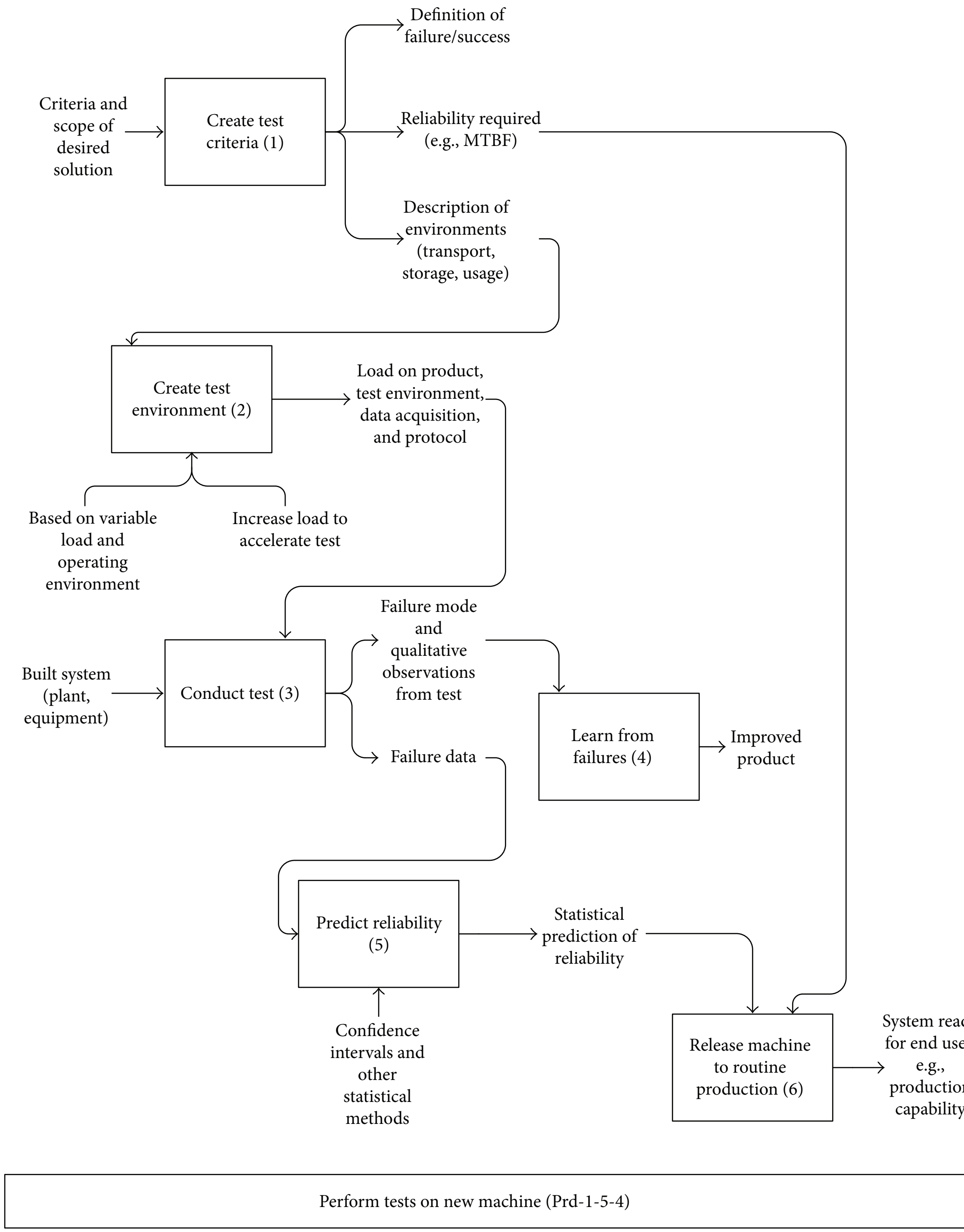

Figure 6: Model for the test activities.

Development of the model system allowed the basic concept of the system to be tested. The model was constructed out of crude materials and was tested under a range of conditions to determine the optimal operating parameters. The full scale vertical screw was designed and constructed based on the results obtained from the model system.

Commissioning was completed by operating the system under a set of conditions established to simulate normal operation. The simulation was completed by assembling the new system directly adjacent to its intended future position in the operational plant. It was wired into the system using all of the final wiring components but was not installed into the process. A feed hopper was fitted to the inlet of the screw to simulate the priority feed system and water and various other components were used to simulate the environment of the reaction chamber. The operation of the vertical screw

Figure 7: Advanced commissioning of vertical feed screw during plant operation. Image shows plant being fed with material via a temporary arrangement while being commissioned. (Photograph by K Lawry and used by permission of Ballance Agri-Nutrients.)

during the advanced commissioning phase can be seen in Figure 7. The process of running the system under simulated operating conditions allowed the full commissioning of the mechanical and electrical systems. It also allowed for the partial commissioning of the operation capacity. During this process it was found that several components did not operate as expected. Changes were made to the system and were re-commissioned without any negative effect to the production capacity of the plant.

The process of commissioning prior to the installation of the vertical screw into the system was extremely successful. Full mechanical and electrical commissioning was completed as the full electrical system was used to drive the advanced commissioning process. The operational testing identified several design flaws in the vertical screw. It also reduced the uncertainty associated with the operation of this new technology.

Advanced commissioning has one significant drawback; it only reduced risk associated with the installation of the new vertical screw. The simulated process cannot represent the real process exactly. There are several factors such as continuous operation in the highly reactive environment that cannot be tested until the system is fully installed. Nonetheless the advanced approach was effective in eliminating latent defects and thereby reduced the overall risk.

5.2. Tiwai Point Ship Unloader. New Zealand Aluminium Smelters (NZAS) in Bluff installed a new ship unloader on the Tiwai wharf for the unloading of alumina and coke from incoming ships. The new unloader produced by Alesa Engineering Ltd. replaced the forty-year-old unloader that was installed when the smelter was first constructed in 1971. The new unloader has a significantly increased capacity capable of discharging at 1,000 tonnes per hour (TPH) of alumina and 600 TPH of coke compared to the old unloader that was only capable of discharging 235 TPH of alumina and 250 TPH of coke [30]. The new ship unloader was installed with the aim of reducing the time required for a ship to spend unloading. Less time spent unloading will mean a more efficient use of shipping resources and the reduction of costs associated with slow turn around (demurrage).

Figure 8: Parallel operation of old (left) and new (right) ship unloaders on the Tiwai wharf. (Photograph by K Lawry.)

Installation and commissioning was completed by Alesa under the guidance of specialist project engineering company Bechtel who work onsite at the Tiwai point aluminium smelter. This process had to be completed under tight constraints as it was critical that there were no process interruptions. The smelter is a continuous process which cannot be shut down or restarted without high associated cost.

It was decided to take a *parallel* approach to commissioning; the old unloader must remain in a fully operational state until the new system has been thoroughly commissioned and proven capable of carrying the full operational load.

Keeping the old ship unloader in an operational state significantly reduced the risk of supply interruptions, but introduced additional concerns relating to the integration of the two systems. Integration of both unloaders on the same wharf was completed by limiting the operation of the old unloader to the north half of the wharf, while the new unloader was installed and commissioned on the south half, as seen in Figure 8. Limiting the old unloader to half of the wharf increased the unloading time as the ship had to be manoeuvred around to allow access to all of the holds. This was taken as a minimal sacrifice to ensure consistent supply.

The main modification that was required for the integration of the new unloader into the existing infrastructure was the installation of a new conveyor system to replace the southern half of the existing wharf conveyor, clearly this has cost implications. This was completed before the new unloader was installed. Both the new and old conveyor systems operated as one continuous conveyor that serviced the new and old unloaders simultaneously. The upgrade of the conveyor acted to integrate the two unloaders into the overall process. The new conveyor and ship unloader were constructed and assembled off site. The units were then transported and lifted into place. The use of pre-constructed assembled units significantly reduced installation time, therefore allowing installation to be completed in the short window between scheduled shipping movements.

Several complications emerged during the commissioning, and these extended the project duration. However the parallel approach meant that these had no impact on the overall production capacity of the smelter. The reduction in unloading capacity caused by the limitation of the old unloader to the north half of the wharf was quickly offset by the high capacity of the new unloader even when it was operating at a reduced output. Parallel commission proved to be a successful method of commissioning as there were relatively minor additional costs and the risk of process downtime was completely mitigated. The old unloader was decommissioned once the new unit was fully operational [31].

6. Discussion

This paper makes several novel contributions. First, it provides a novel conceptual framework for the commissioning process. The model represents the decision making within the process, the broader context in which plant commissioning occurs, as well as making provision for the finer details. The novelty is creating a structured representation of the commission process, where models are otherwise sparse. Commissioning is generally an ad hoc process, and the value of this new framework is that it provides a structured theoretical foundation for this important activity.

A second contribution is the categorisation of commissioning into three main types: advanced, parallel, and direct. This exposes the variability of strategies within the commissioning process, so it becomes apparent that there is not merely one universal approach to commissioning. Achieving this adds choice to the project planning. It makes it clear that there are choices that practitioners can make, and stating these choices encourages a thoughtful consideration of the planning and resource implications thereof. This categorisation thus adds richness to the conceptual model and makes the decision points more explicit, without being prescriptive.

A third contribution is the development of a model for use by practitioners. The model captures and represents the proposed situational variables (contingency factors) involved in the process. This is valuable for informing the decision making of practitioners. The applicability of the model has been demonstrated by case studies.

A fourth contribution is the integration of commissioning into other management models. The model provides integration with the "risk management" and "project management" disciplines. This is valuable because it shows practitioners how commissioning may be approached in a more holistic manner. The commissioning model is also integrated into a wider model for the development of production plant, and thereby into "manufacturing engineering" including quality and lean manufacturing. Space does not permit full description of this integration, but the point is that the work shows that this integration is indeed feasible. The model is represented in IDEF0 notation, which is a production engineering notation, meaning that it is readily comprehendible in that context.

Overall what has been achieved is to replace the otherwise ad hoc process of commissioning with a systematic process complete with proposed decision factors and internal models of causality. There are implications for practitioners in the model, in the form of flowcharts identifying the critical success/failure factors for commissioning. Thus tentative recommendations can be made for the best commissioning approach for a given situation.

There are also implications for further research. The model is at least partly conjectural, and further research could be directed at establishing the validity of the proposed causal relationships. Another strand of research could be directed at further refinement of the model, and its extension deeper into specific cases, that is, further investigation of the situational variables.

7. Conclusion

Commissioning is extremely valuable to all projects but is poorly defined in the project management body of knowledge. The existing literature on commissioning is focussed on specific tasks, and holistic perspectives are lacking. This work has reconceptualised commissioning and shown that it is possible to identify three main types of commissioning (direct, parallel, and advanced) and construct a generalised conceptual framework around them. This approach to commissioning has been demonstrated by application to case studies.

The value of this work is that it presents a different and more structured way of thinking about commissioning. This allows for a more critical examination of how to complete the commission for a particular project, and ultimately the potential for a better commissioning outcome for practitioners. For theorists the benefit is that a generalised model has been developed, thus a foundation for future advancement of the subject. We have shown that the commissioning activities can be integrated into the risk management, project management, and production engineering bodies of knowledge.

Acknowledgments

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