AACE INTERNATIONAL RECOMMENDED PRACTICE

135R-24

SYSTEM DYNAMICS MODELING TO DEMONSTRATE ENTITLEMENT TO PROJECT DISRUPTION COSTS

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TCM Framework: 6.4 – Forensic Performance Assessment

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1. INTRODUCTION

This recommended practice (RP) of AACE International provides guidance on using system dynamics modeling (SD) to produce expert evidence to support entitlement to compensation for claims arising from disruption in construction and engineering projects. System dynamics assists in identifying and quantifying the root causes, damages, and delays resulting from project disruption.

This RP is intended to provide guidelines for a suggested process using the system dynamics modeling approach to identify the root causes, damages, responsibilities, and delays resulting from project disruption. The system dynamics process applies across all common engineering and construction contracting strategies and delivery methods, and it can be particularly useful in identifying and quantifying the cumulative impact of disruption.[1] This recommended practice includes the concepts reviewed and approved by the cost engineering industry using good industry practices and recommendations, and it is relevant to all project stakeholders, whether owner, designer, contractor, subcontractor, construction manager, or others. Although this recommended practice is written in the context of a contract between an owner and a prime contractor, it applies to all parties contracted to perform work on a project, including subcontractors and suppliers.

1.1. Disruption

Managing projects involves a complex and integrated array of decisions, actions, and communications necessary to complete the work successfully. When projects are subjected to unanticipated events or conditions (UECs), disruption usually occurs.

Disruption is defined as:

> "An interference (action or event) with the orderly progress of a project or activity(ies)", which "manifests itself primarily as adverse labor productivity impacts." [1]

Productivity losses are known to regularly occur in engineering and construction projects, and the more complex the project, the risk of productivity losses increases. Productivity losses resulting from disruption can often occur without warning or a seemingly plausible explanation. Demonstrating the reasons for what caused productivity losses and their related costs is one of the most contentious management aspects of the construction industry.

Expanding on the definition of disruption, it can be categorized into two types: direct and indirect. Both types of disruption can occur on engineering and construction projects and, when present, can cost a contractor millions of dollars.

Direct disruption is defined as:

> "The immediate and direct disruption resulting from a change[2] or other influence that lowers productivity in the performance of the changed or unchanged work. Direct impact is considered foreseeable and the disrupting relationship to unchanged work can be related in time and space to a specific change. Direct disruption may result in a delay to the work, whether on or off the critical path(s)." [1]

As the definition indicates, direct disruption affects unchanged or previously approved changed work that can be related in time and space to a specific event or condition.

[1] See AACE Recommended Practice 130R-23 for further discussion on demonstrating the cumulative impact of disruption. [2]

[2] In the context of disruption, the term *change* is understood as any event or condition that forced the contractor (or a subcontractor or supplier) to deviate from their current plan on how to execute the works.

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On the other hand, indirect disruption is more difficult to identify, quantify, and trace back to its causes. Indirect disruption, also known as *cumulative impact*, is defined as:

1. "The unforeseeable disruption of productivity resulting from the synergistic effect of an undifferentiated group of changes.
2. The impact of unchanged work (throughout all or a portion of a project and not necessarily temporally or physically close) that is not attributable to any one change but flows from the synergy of the number and scope of changes issued on a project." [2]
3. The impact may result in a delay to the work, whether on or off the critical path.

As noted, both direct and indirect disruption are caused by *changes*, i.e., by unanticipated events or conditions that force the contractor to change what it is contractually bound to build, and/or how it intends to do so. Impacts on engineering and/or construction projects resulting from productivity losses and/or rework are among the most difficult types of change to demonstrate, since they often occur without warning or a seemingly plausible explanation.

1.2. Demonstrating Entitlement: Causation

The key objective of any disruption claim is to prove that the claimant[3] is entitled to receive compensation for losses incurred on a project as a result of impacts caused by other parties. Thus, the effectiveness of a disruption assessment method needs to be measured in terms of how well it helps to prove this entitlement.

In a disruption claim, the claimant (usually the contractor)[4] should successfully complete seven tasks in order to demonstrate entitlement to the requested costs:

1. Causal event occurrence.
2. Adherence to contract change notice requirements.
3. Contractual entitlement to request a contract change or make a claim.
4. Causation.
5. Prudent effort to mitigate any impacts.
6. Assignment of responsibility.
7. Quantification of impacts. [3, p. [illegible]]

A full description of these tasks can be found in AACE Recommended Practice 120R-21, Demonstrating Entitlement for Contract Change Orders or Claims – As Applied in Engineering, Procurement, and Construction. [3] Among these steps, establishing causation is often the most problematic, since linking productivity losses and their related costs to the events and conditions that caused them is one of the most contentious management aspects in the construction industry:

> "Unlike direct costs, lost productivity is often not tracked or cannot be discerned separately and contemporaneously. As a result, both causation and entitlement concerning the recovery of lost productivity are difficult to establish. Compounding this situation, there is no uniform agreement within the construction industry as to a preferred methodology of calculating lost productivity." *[4, p. 1]*

Construction delay and disruption disputes routinely involve multiple causes, many of them with knock-on, overlapping, and/or interrelated consequences (often referred to as *ripple effects*). Consequently, when addressing causation in delay and construction claims, analysts are often confronted with a complex set of multiple, crisscrossing chains of events, forming a whole network of causes and effects: "The chain of causation is a handy

[3] While the terms *claimant* and *respondent* are often reserved for formal dispute settings, in this document they are also meant to apply to all other claim settings (like stakeholder negotiations).

[4] While most disruption claims may be brought forth by contractors (against owners), subcontractors can also claim against main contractors, and owners can counter-claim against contractors.

expression, but the figure is inadequate. Causation is not a chain but a net." [5, pp. 368-369] As outlined in AACE International Recommended Practice 25R-03, conventional methods sometimes struggle to adequately address this complex interplay of causes and effects, hindering an effective, comprehensive disruption assessment. [4]

An evaluation of which productivity loss analysis methodologies are generally considered most reliable can be found in Figure 1 below. It shows how methods that use more contemporaneous project documentation require more effort (and are thus more costly), but that they also deliver more reliable (less uncertain) results.

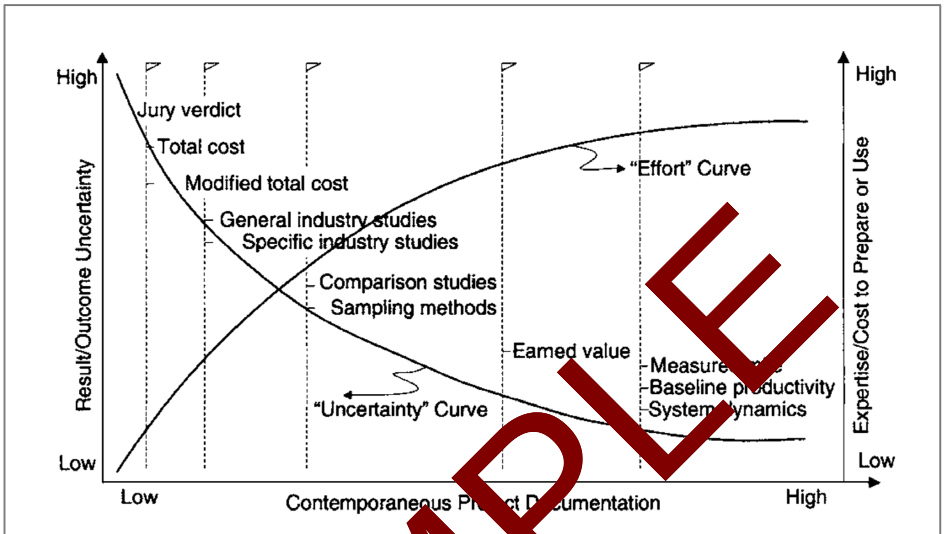

Figure 1: Relative reliability of methods for quantifying lost productivity [6, pp. 47, Figure 2]

System dynamics is generally considered to be among the most reliable methods for quantifying productivity losses because it can not only determine the ultimate cost and time impacts caused by productivity losses, but it also explicitly traces and quantifies the chain of causation from these impacts to the events that caused them. This capability becomes particularly helpful when disruption due to cumulative impact is suspected.

1.3. System Dynamics Modeling

System dynamics was originally developed by Jay W. Forrester at the Sloan School of Management (Massachusetts Institute of Technology) in 1958. It is a simulation-based approach that "…combines the theory, methods, and philosophy needed to analyze the behavior of systems in not only management, but also in environmental change, politics, economic behavior, medicine, engineering, and other fields", using "concepts drawn from the field of feedback control to organize available information into computer simulation models." [7] In other words, system dynamics is used to better understand the complex (and sometimes even counterintuitive) behavior of systems over time.

One key application area of system dynamics is the forensic analysis of delay and disruption in complex engineering and construction projects. System dynamics was first applied in this capacity to successfully support a delay and disruption claim brought by a defense contractor against the US Navy in 1976 [8]. This initial success then paved the way for the use of system dynamics in dozens of additional delay and disruption claims worldwide.

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1.4. When (and Why) to Use System Dynamics

Most disruption assessment methods are limited to quantifying productivity losses based on informed estimates of their timing and of the extent to which work was directly affected. What sets system dynamics apart is its unique ability to help demonstrate causation: while other methods are limited to informing the analyst about when the productivity losses occurred (and about the associated cost and/or schedule impacts), system dynamics helps to pinpoint the most likely causes for the productivity losses, and how much each causal event contributed to each productivity loss (when there is more than one). Understanding what factors caused a productivity loss and the associated apportionment of responsibility is essential, especially when there could be more than one party to the contract bearing that responsibility, and when the impacts of multiple disruptive events and conditions overlap.

While system dynamics is a powerful tool, it is not always the optimum choice for every project. Figure 2 shows the factors that should be considered when considering system dynamics as a disruption assessment method:

a) **Size matters:** System dynamics modeling is focused on analyzing large, complex projects with numerous activities, workers, and stakeholders. This is because the method works by simulating the dynamics of groups of people working on groups of activities, and these groups need to be of a minimum size for the analysis to be statistically reliable.

b) **Level of disruption:** System dynamics can be more complex and time consuming to set up than other disruption assessment methods. So, it is best used when other methods are unlikely to meet the requirements of demonstrating entitlement, which typically occurs when projects are heavily disrupted and both parties bear some responsibility for it (and so they are unable to establish causation and fairly allocate responsibility).

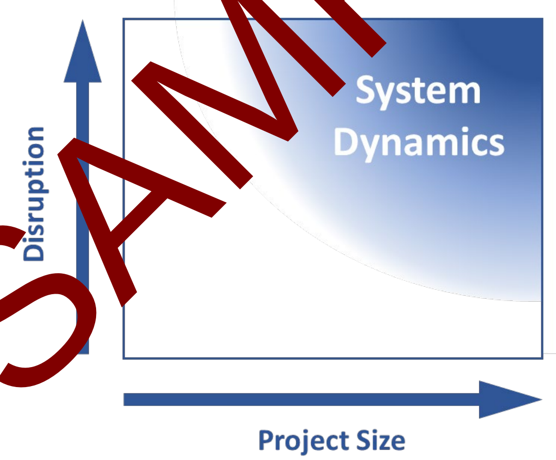

Figure 2: Optimal Application Space For System Dynamics (Adapted from [9]).

In order to produce reliable results, system dynamics simulation models need to be supported by a broad range of project data,as discussed in more detail in Section 4. However, it should be noted here that system dynamics disruption assessments are quite resilient in the face of incomplete datasets, because of the method's ability to (a) draw from multiple data and information sources and (b) validate key modeling assumptions not fully supported by data (see Section 2.4.1.) Therefore, deciding whether to employ system dynamics to support a disruption claim in the face of incomplete data is hardly ever a black or white matter, since in most cases system dynamics will still use a broader range of project data than alternative disruption assessment methods.

To summarize: System dynamics is a powerful disruption assessment method, ideally suited to determine causation and thus quantify and allocate responsibility for losses experienced in large, complex engineering and construction projects that have been heavily disrupted.

1.5. Disruption vs. Delay

Delay and disruption may be two clearly distinct concepts, but they are two sides of the same coin: they are often both cause and effect of each other, so that disruption can lead to delay, and delay can lead to disruption. [10, p. 10] System dynamics simulation models capture this characteristic of engineering and construction projects by including delay as both a potential cause and a potential consequence of disruption. Thus, system dynamics simulation models analyse disruption and delay jointly.

System dynamics assessed both disruption and delay from the beginning (the 1976 claim against the US Navy). While it is true that the literature since then has focused mainly on applying system dynamics to assessing disruption, all its forensic simulation models have continued to assess both disruption and delay.

Most often, delay assessments emanating from system dynamics models have been used to support forensic delay analyses based on some variant of the critical path method (CPM). However, in heavily disrupted projects, CPM experts sometimes find that their analyses are unable to capture the full delaying impact of certain types of disruptive events. In these cases system dynamics can be (and has been) used as the lead delay assessment method. [11]

Note that CPM and system dynamics assess delay from very different perspectives: CPM proceeds based on a detailed precedence map of construction activities, whereas system dynamics focuses on the labor productivity dynamics affecting larger groups of such activities. Thus, when both methods are applied to the same project, analysts should expect their results to be somewhat different. Nonetheless, if both analyses have been conducted properly, their results will be found to be complementary and their differences fully explainable.

Finally, note that delay claims are executed under different contractual and legal boundaries and constraints than disruption claims (for example, both are usually governed by different contractual clauses), and these differences may vary by legal jurisdiction (among other issues). While the analytical approach used to apply system dynamics to the assessment of delay and disruption is mostly common, this recommended practice is focused solely on the latter.

1.6. Structure of This Recommended Practice

Section 2 describes the characteristics that a system dynamics forensic project simulation model should exhibit.[5] This section does not cover *how* to build such a model; this is considered to be basic information that any system dynamics expert should already have.

Section 3 describes the recommended analytical process to be followed to produce a disruption assessment using the system dynamics method.

Section 4. describes the validation and testing processes to be followed to maximize the reliability of the assessment.

[5] The text does not cover how to build a generic system dynamics simulation model, it only touches upon the particular characteristics of the simulation models used to forensically assess the performance of engineering and construction projects.

The recommended practices detailed herein apply to the development of system dynamics simulation models to be used to support forensic disruption assessments.They complement (and when in conflict, supersede) modeling best practice recommendations found in the general system dynamics literature.[6]

2. RECOMMENDED PRACTICE: CHARACTERISTICS OF THE SIMULATION MODEL

2.1. The Project Dynamics Framework (PDF)

System dynamics simulation models are centered around causation: The purpose of the models' equations is to describe how the different variables present in a project interact with each other, thereby determining its performance.

The causal framework (i.e., the qualitative blueprint) for forensic project simulation models was originally developed in the late 70s by Pugh Roberts Associates in the course of building a model to support a delay and disruption claim against the US Navy [8]. The success of this first claim led experts to adopt this model as a blueprint to build other similar ones for other projects; since then, simulation models based on the same qualitative causal framework (the project dynamics framework [7], or PDF) have been used as the foundation for proactive analyses to help prevent and mitigate disruption on ongoing projects, and for retrospective assessments to support delay and disruption disputes. System dynamics simulation models have been used to assess projects in all kinds of industries (construction, automotive, aerospace, software, IT systems, shipbuilding, etc.) and in all continents. Its continued successful use and broad range of application proves that this underlying framework captures the essence of how projects work, including: how disruption arises, how it spreads, how managers react when faced with it, and how disruption and delay reinforce each other.

A graphical representation of the PDF is shown in Figure 1 where each arrow represents a causal connection. The framework captures how work gets done, how rework arises, how labor can be restricted, how delays are created, and acceleration measures are introduced, the different ways in which productivity losses can be created – and how all these factors interact. A more detailed description of the PDF can be found in Appendix A.

[6] General best practice recommendations can be found in the system dynamics literature. For a general textbook on system dynamics modeling, see, for example, Sterman, John D., "Business Dynamics: Systems Thinking and Modeling for a Complex World", Irwin McGraw-Hill (2000). [12]

[7] Originally, this causal framework was called *the* Rework Cycle". The name has been changed to avoid the common misconception that the framework is focused only on the dynamics involving rework. The term *rework cycle* is maintained to refer to just to the subset of the PDF that contains the four stocks of work (*work not yet started*, *work complete*, *rework to be found* and *rework to do*) and the rate variables connecting these.

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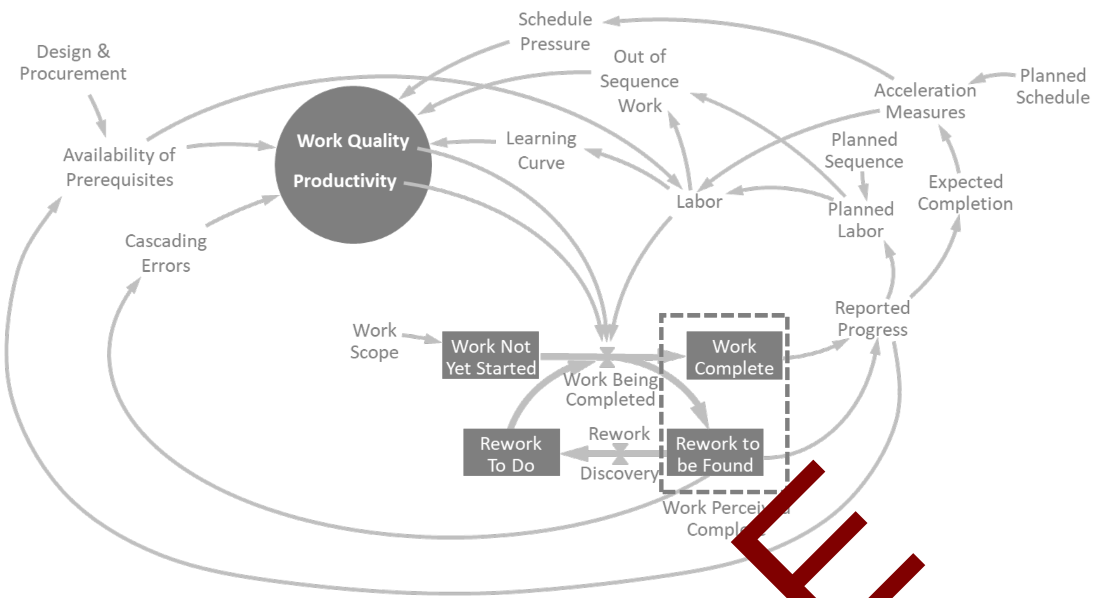

Figure 3: The Project Dynamics Framework[8]

All projects are unique, and thus each individual expert facing a disruption claim in the past has had to translate this framework into a distinct simulation model comprising a distinct set of equations. However, the causal blueprints underpinning all reported forensic project simulation models to date have been based on the PDF. It is therefore strongly recommended that future simulation models be equally based upon this framework as much as possible, and that any exceptions be well-reasoned and documented.

It should be noted that the diagrams used throughout this document show one particular version of the PDF. This section focuses on the core tenets of the framework; however, these are few and basic in nature, thus leaving some room for variability from project to project.

2.1.1. Productivity and Rework

While rework is sometimes considered a type of productivity loss, system dynamics makes a clear distinction between productivity and work quality (which causes the need for rework). It is true that the same loss factors impact both, but productivity losses are felt when they occur, whereas errors and omissions can remain hidden a long time before they are discovered and resources can be allocated to execute the necessary rework. Figure 4 shows how rework is captured in the PDF: how part of the work being completed contains errors and omissions and ends up in the stock[9] of Rework to Be Found, how the errors and omissions are found and eventually remedied.

This late discovery and execution of rework is a regular occurrence in complex engineering and construction projects, causing both time and cost overruns. As common examples, note extensive rework during testing and commissioning, or long punch-lists near project completion. Rework is usually significant enough to require that it be assessed separately from (even if closely tied to) productivity losses.

[8] This graphical representation of the causal framework underlying system dynamics simulation models, as well as any variants of it shown hereafter, are based on the original diagrams used by Cooper (1980). [8]

[9] In system dynamics, a stock is a state variable that represents an accumulated quantity at any given time. It changes only through inflows (adding to it) and outflows (reducing it). Stocks act as the system's memory, capturing the results of past actions and influencing future behavior. In construction, examples include work backlog, or workforce levels.

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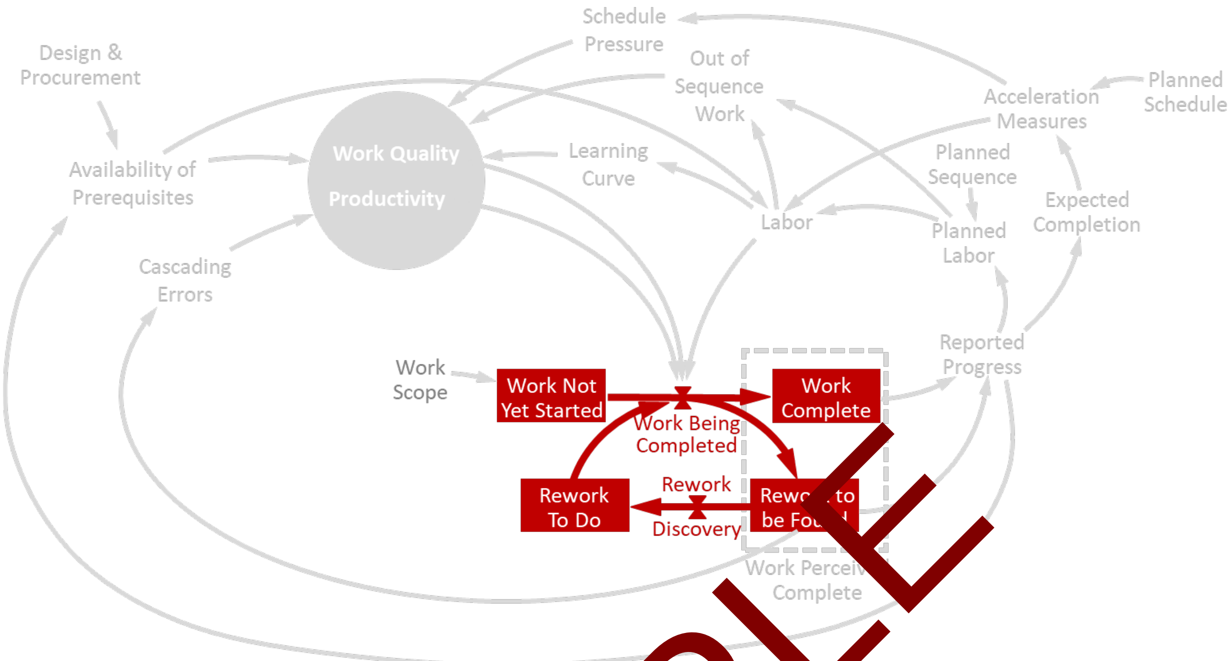

Figure 4: The Rework Cycle: How Work is Done and Re-Done.

The rate with which errors and omissions are discovered is typically a function of other project variables—for example, the discovery of design errors is usually accelerated as construction progresses.

2.1.2. Productivity Losses

Many factors can generate disruption on a project. Many studies on this subject exist, and several professional organizations offer lists and propose types of productivity losses caused by each. For more information on productivity loss factors, refer to AACE International, Recommended Practice No. 25R-03, Estimating Lost Labor Productivity in Construction Claims. [4] Table 1 lists some of the most common factors causing productivity losses on construction projects.

- Absenteeism and the missing man syndrome
- Acceleration (directed or constructive)
- Adverse or unusually severe weather
- Availability of skilled labor
- Rework and errors
- Competition for craft Labor
- Craft turnover
- Crowding of labor or stacking of trade
- Deficient shop drawings
- Design errors and omissions
- Dilution of supervision
- Failure to coordinate trade contractors, subcontractors and/or vendors
- Fatigue/overtime
- Excessive Inspection
- Schedule pressure
- Labor relations and labor management factors
- Learning curve
- Material, tools, and equipment shortages
- Availability of work from upstream work phases
- Quality of work from upstream work phases
- Overmanning
- Permitting delays
- Worker morale
- Project management factors
- Out-of-sequence work
- Rework and errors
- Safety issues
- Site logistics
- Site or work area access restrictions
- Site conditions
- Untimely approvals or responses

Table 1: Common Project Productivity Loss Factors. [4]

Note that many of these factors are driven by project conditions: for example, working out of sequence often results from a management decision to accelerate the work. This is captured by the PDM, as shown graphically in Figure 5, and described in more detail in Appendix A.

To save assessment time and effort and to make simulation models more manageable, system dynamics simulation models should only include the productivity loss factors that actually impacted project performance and those that may be required to produce other scenarios relevant to the claim. The process for selecting the appropriate productivity loss factors to be used in a particular simulation model is described in Section 3.3.1.

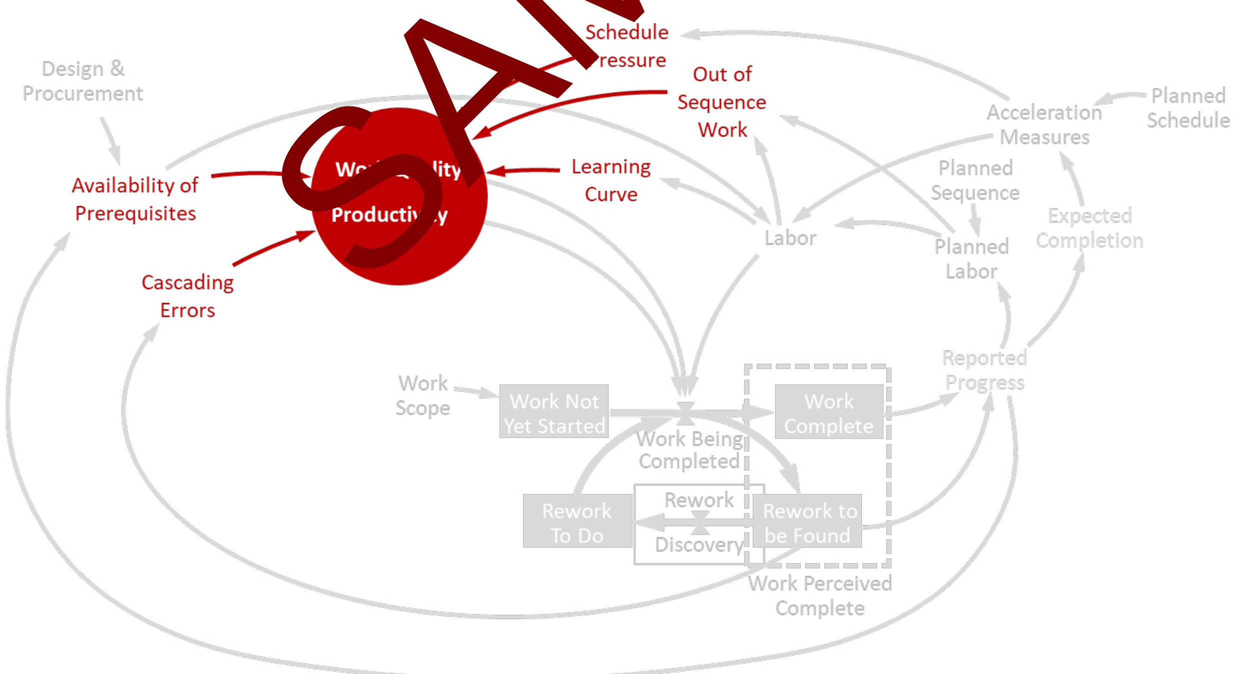

Figure 5: All Significant Productivity Loss Factors are Included in an Assessment