

# OPERATIONALISING TRANSFORMATION– FLOW–VALUE IN LEAN CONSTRUCTION VIA SMART-ENABLED AWARENESS

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## ABSTRACT

Lean Construction’s transformation, flow, and value (TFV) objectives rely on teams maintaining sufficient situational awareness (SA) of production conditions at the point of decision making. In construction projects, this awareness is often uneven and unmanaged, leading to weak commitments, unstable flow, and value loss despite the use of established Lean planning and control practices. This paper develops a mechanism-based explanation that treats SA as a controllable production condition. The theory is derived from a synthesis of Lean Construction and SA literature, together with observed limits of digital sensing and procedural coordination. Situation Monitoring, Analysis, and Reporting Teams (SMART) are positioned as a Monitor–Analyse–Report sequence that supports SA within existing Lean routines. The analysis shows that managing SA upstream improves downstream production outcomes. Improved perception reduces specification gaps and rework, stabilising Transformation. Shared comprehension increases early constraint visibility and coordination reliability, stabilising Flow. Short-horizon projections enable timely resequencing and buffer adjustments, protecting Value under change. Positioning SA as a production condition creates a practical opportunity to stabilise Lean performance by improving decision quality upstream rather than correcting failures downstream. The paper concludes with testable propositions and guidance for embedding SMART into TFV-based production planning and control.

## KEYWORDS

Lean construction, Transformation-Flow-Value, situational awareness, SMART, production control.

## INTRODUCTION

Construction projects function as a dynamic, interdependent and partially observable environment. Project site conditions change faster than plans can stabilise, leading to deviations between the plan and the actual state. This results in decisions on work release, handoffs, and priorities being made with incomplete SA, leading to rework, unstable handoffs, and plan churn. SA is defined as per Endsley's SA model, which states that it is “perception of elements within a volume of time and space, comprehension of their meaning and projection of their state onto the near future”(Endsley, 1995). Production control depends on releasing work, coordinating handoffs, and sequencing tasks under uncertainty. The quality of SA directly limits the effectiveness of any production management approach, including lean construction. Lean

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construction is explicitly positioned as the production management approach to address these production problems. Lean defines production intent through TFCV and operationalises it through practices such as last planner, takt planning, pull, and visual management (Ballard, 2000; Koskela, 2000). However, these practices implicitly assume that teams share an accurate and aligned SA of the different project situations at the time decisions are made. When these assumptions are tested in dynamic project settings, lean planning and control mechanisms struggle to achieve the intended production outcomes (Hamzeh et al., 2012; Tommelein, 2015).

This gap between lean's intent and its execution points to a missing mechanism rather than a missing principle. TFCV specifies what production should achieve, but it does not specify how the SA required to apply TFCV-based planning and control is continuously generated and aligned in live projects. Existing responses to this gap have largely focused on digitalisation. Technologies such as BIM, IoT, and Digital Twins increase data availability and enhance perceptions of site conditions (Sacks et al., 2020). However, these systems do not, by themselves, ensure shared comprehension or reliable near-term projections, especially when information is fragmented, delayed, or unevenly interpreted across roles as they were never designed to create SA. As a result, more data does not automatically lead to better lean decisions. Without structured sensemaking and communication, increased perception-level information can overload teams while leaving key production decisions unsupported (Martinez et al., 2023). What is missing is an explicit socio-technical mechanism that converts signals into shared, decision-ready situational understanding at the moments when Lean decisions are made. In this paper, this mechanism which is reported as Situation Monitoring, Analysis, and Reporting Teams (SMART), a structured routine responsible for synthesising and communicating situational insights at key Lean decision points without replacing them. SMART is not a new planning system, not an additional reporting layer, and not a relabelling of existing Lean routines such as huddles or visual management. Instead, it operates as a dedicated mechanism for generating and aligning shared situational awareness across roles.

This study suggests that while Lean describes what production must achieve through TFCV, SMART specifies how the requisite SA can be achieved in a methodical manner without changing Lean procedures. SMART is a socio-technical mechanism that monitors site conditions with digital and human inputs, interprets them using cross-role sensemaking, and reports via brief role-specific narratives that capture site conditions and consequences. Rather than introducing a new planning system, SMART incorporates lightweight monitoring and sensemaking into positions such as site engineer, trade foreman, and planner, in line with Lean techniques such as lookahead, make-ready, weekly work planning, and takt control. It provides verified cross-role situational narratives and assigns unambiguous responsibilities for SA, addressing its dispersion in Lean while working within current decision windows to ensure awareness and commitment. Improved perception lowers specification-reality gaps and rework, which improves transformation reliability. Increased constraint visibility, lower interface variability, and better PPC and takt adherence all contribute to increased flow stability. Explicit projection enables timely resequencing and buffer insertion, resulting in improved value delivery.

This study presents a conceptual integration of TFCV and SA. SMART operationalises SA conditions that are assumed but not explicit in Lean. The study uses a theory-building approach. It combines a structured synthesis of Lean Construction and SA literature with abductive reasoning from coordination and planning failures. The analysis selects prior work on TFCV, planning and control, and SA in dynamic systems. It derives mechanisms by linking recurring issues such as late constraint discovery and plan instability to SA components. These components include perception, comprehension, and projection. The study then refines these mechanisms into testable propositions grounded in prior research and repeated failures. The analysis maps SA perception to transformation dependability. It maps SA comprehension to

flow stability. It maps SA projection to value protection under disruption. Prior Lean Construction research has focused on improving planning and control practices (e.g., Last Planner, takt, pull) or increasing information availability through digital systems such as BIM, IoT, and Digital Twins (Ballard, 2000; Sacks et al., 2020; Seppänen et al., 2010). Research on SA in construction has similarly focused on safety or individual cognition, with limited integration into production theory (Halttula & Seppänen, 2022). By contrast, this work positions SA as a core production requirement, embeds it within TFFV, and specifies SMART as the socio-technical mechanism that produces and aligns SA at Lean decision points. The contribution is therefore not an additional tool, but a clear specification of how SA enables Lean production under uncertainty. This paper does not introduce a new planning system; rather it specifies the mechanism through which the SA required for TFFV-based planning and control is generated and aligned in practice.

The remainder of the paper studies TFFV limitations in lean construction, reviews SA theory, introduces SMART as an operational mechanism and develops mechanism-based explanation linking SA capabilities to TFFV production outcomes.

## **TFFV IN LEAN CONSTRUCTION AND ITS PRACTICAL LIMITATION**

Lean construction is grounded in production theory, which frames construction as a system of transformation, flow, and value (TFFV), operationalised through planning and control practices.

Koskela (2000) reframed construction production beyond transformation to include flow and value, establishing TFFV as a theoretical foundation for analysing production performance. TFFV specifies what production should achieve but does not specify how situational information is generated and aligned under uncertainty. Subsequent work positioned TFFV as the conceptual basis of Lean Construction and highlighted limitations of traditional approaches that neglect flow and value (Koskela et al., 2002) but remained at a conceptual level and left implicit the situational understanding required in practice. Operationalisation of TFFV has focused on planning and control systems such as the Last Planner System (Ballard, 2000). This system improves workflow reliability through constraint management and commitment-based planning. It assumes that constraints can be identified and assessed with sufficient accuracy. It does not specify how this understanding is formed and aligned across roles. Extensions such as the Lean Project Delivery System embed TFFV across project phases but similarly do not specify how teams interpret and act on uncertainty at decision points (Ballard & Howell, 2003).

Empirical studies document recurring limitations in Lean execution, particularly late constraint identification that undermines workflow reliability (Hamzeh et al., 2012), often treated as procedural rather than perceptual or interpretive limitations. Technical integrations, such as combining LPS with location-based systems, improve forecasting but assume that information is correctly interpreted and aligned across participants (Seppänen et al., 2010). Reflective accounts also document persistent coordination and variability challenges in Lean implementation (Tommelein, 2015), without isolating situational understanding as a distinct production variable. A related concept in production theory is the “status of the system”, representing the current state of work, resources, and constraints required for pull-based control. In construction, this status is not directly observable and must be constructed from distributed signals, reinforcing that production control depends on how accurately and timely this information is perceived, comprehended, and projected across actors.

Overall, the literature establishes TFFV as a production theory and Lean methods as its operationalisation, while documenting recurring breakdowns in coordination and flow reliability. Across these studies, an implicit assumption persists: teams operate with sufficiently accurate and shared situational awareness. However, no explicit mechanism exists for generating and aligning such awareness in dynamic project environments. This gap motivates

the present work, which treats SA as a necessary production condition and introduces SMART to operationalise it.

## **SA AS A PRODUCTION REQUIREMENT**

SA has been studied in dynamic, time-critical domains. This section reviews its foundations and limitations in construction production. Endsley (1995) defines SA as perception, comprehension, and projection, establishing it as a prerequisite for decision-making in dynamic systems. However, the model is individual-centric and does not address how SA is shared or maintained across multiple actors in production settings. Distributed SA extends this view by locating awareness across people, artefacts, and systems (Stanton et al., 2006), but remains descriptive and does not specify how SA is aligned at decision points. Digital construction research focuses on improving SA through data-centric systems such as Digital Twins, BIM, IoT, and positioning systems (Sacks et al., 2020; Reinbold et al., 2019; Zhang et al., 2021). These approaches improve perception by increasing data availability and visibility. Tools integrating planning signals further enhance awareness (Martinez et al., 2023). However, these approaches remain focused on perception, with limited support for detecting weak signals or interpreting emerging situations, constraining anticipation and response. Organisational studies show that coordinated action depends on shared sensemaking rather than raw information (Weick, 1995), highlighting that SA includes collective interpretation and projection.

Resilience engineering conceptualises system performance in terms of four capabilities: monitoring current conditions, anticipating future states, responding to variability, and learning from past outcomes (Hollnagel, 2013). These capabilities align with SA as perception, comprehension, and projection, but extend it by emphasising system-level adaptation under uncertainty. In parallel, production theory introduces the concept of the “status of the system”, defined as the observable state of work, resources, and constraints required for effective pull-based control (Hopp & Spearman, 2011). In construction, this status is not directly observable and must be constructed from distributed signals across actors. Taken together, these perspectives indicate that production performance depends not only on system design but on how accurately and timely the system state is monitored, interpreted, and projected across roles. In this context, SA provides the mechanism through which the ‘status of the system’ is constructed from distributed signals prior to pull-based decisions and aligns with resilience functions such as monitoring and anticipating, which SMART operationalises within Lean decision routines. This reinforces the need for an explicit mechanism to generate and align shared SA within Lean production systems.

Overall, the literature establishes SA as necessary for decision-making in dynamic, distributed systems, but does not specify production-integrated mechanisms for maintaining shared SA. This gap motivates the introduction of SMART as an operational mechanism within Lean production systems.

## **SMART AS A SA MECHANISM**

SMART is positioned as a socio-technical mechanism for implementing SA in Lean decision contexts by structuring how information is monitored, analysed, and reported across roles. As seen in Figure 1, SMART is integrated into Lean decision windows such as lookahead planning, make-ready, weekly work planning, and daily huddles to ensure SA is available at the point of commitment. SMART operates as a Monitor-Analyse-Report cycle that transforms distributed project information into decision-relevant SA. While make-ready planning identifies and removes constraints, and visual management or huddles monitor task status and commitments, SMART integrates distributed data into causal, role-specific narratives explaining deviations

and downstream impacts. It operates as an enhancement rather than a substitute, improving the quality and alignment of situational understanding at decision points.

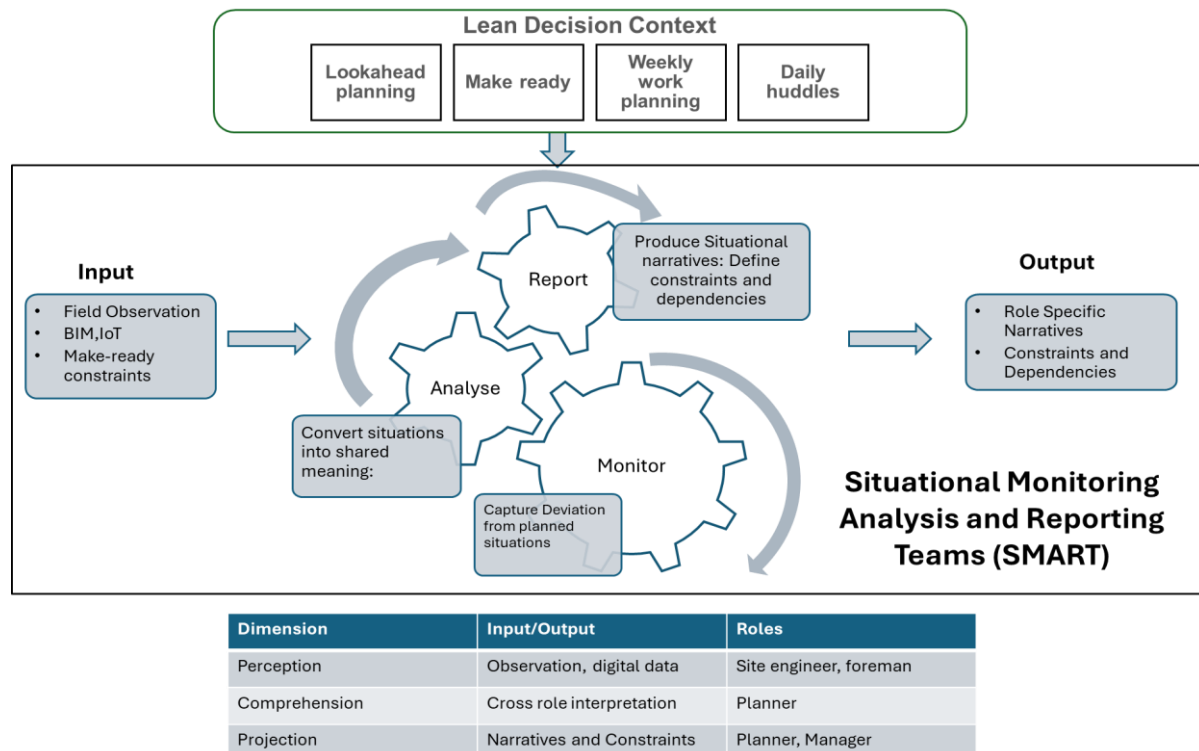


Figure 1: SMART as a socio-technical mechanism for generating shared SA within Lean decision contexts.

Monitoring detects differences between planned and actual conditions using human observations and digital data, expanding the scope and timeliness of observable conditions, though signals remain fragmented. Analysis applies cross-role interpretation to translate signals into shared meaning and align technical, organisational, and sequencing conditions across roles. Reporting produces concise, role-specific outputs indicating constraints, dependencies, and short-term consequences, supporting coordination and projection at decision points. SMART outputs consist of short, structured reports capturing detected constraints, causal explanation, and short-horizon implications for downstream work, generated prior to lookahead and weekly work planning discussions and updated in daily huddles to support commitment decisions. SMART is a distributed, role-based routine embedded in Lean planning cycles, where site engineers and foremen record conditions, planners assess constraints and interdependencies, and reporting converts these into decision inputs. It captures what occurred, explains why deviations arose, and identifies impacts, while surfacing gaps between assumptions and field conditions, including weak signals. SMART operates alongside BIM dashboards and visual boards, improves planning by making failures explicit and enabling adjustment of assumptions, does not change decision authority, and is validated through cross-role confirmation of constraints and dependencies.

SMART generates validated situational narratives and explicit constraint representations to aid Lean planning and control. SMART combines distributed information into shared, decision-ready situational understanding across roles. Figure 1 summarises how perception is facilitated by digital inputs and observation, comprehension by cross-role interpretation, and projection by narrative reporting. This process aligns SA generation with Lean decision processes, as summarised in Table 1.

Table 1: SMART compared with existing Lean routines

| Element    | SMART                                               | Existing Lean routines           |
|------------|-----------------------------------------------------|----------------------------------|
| Focus      | Situational understanding (causes and implications) | Task status and commitments      |
| Inputs     | Field observations and digital signals              | Plans, constraints, task updates |
| Outputs    | Causal narratives and short-horizon projections     | Commitments, constraint lists    |
| Roles      | Explicit SA responsibility across roles             | Implicit, role-dependent         |
| Timing     | Before decision points                              | During planning routines         |
| Validation | Cross-role confirmation                             | Limited or implicit              |

## INTEGRATING TFV AND SA THROUGH SMART

This section develops the paper's key theoretical integration. It argues that lean construction's TFV framework specifies the production objectives but implicitly relies on a level of SA that is not guaranteed in dynamic environments. SMART provides the operational mechanisms through which this SA can be generated and aligned to support TFV in practice. Figure 2 below summarises the integration.

### TFV OBJECTIVES AND THEIR DEPENDENCE ON SA

TFV framework defines production in terms of transformation, flow and value. These dimensions specify what the production should achieve, but do not explain how decisions are made under uncertainty. In practice, production control depends on forming sufficiently accurate and shared SA of the evolving situations. When SA is weak or misaligned, decisions within TFV-based planning and control may be misinformed in practice. Transformations are executed under incorrect assumptions about readiness; flow may degrade as constraints and dependencies are introduced late, and value may be compromised when downstream impacts are recognised only after disruptions occur. These failure modes occur even when lean planning and control methods are applied, indicating a missing link rather than the failure of TFV logic.

Figure 2 makes this link explicit by separating the TFV and SA layers. Transformation, Flow, and Value are shown as production objectives whose achievement is influenced by the quality of SA at the point of decision-making. This separation clarifies that the TFV informed production control is shaped by the cognitive and information substrate that lean theory largely assumes rather than specifies.

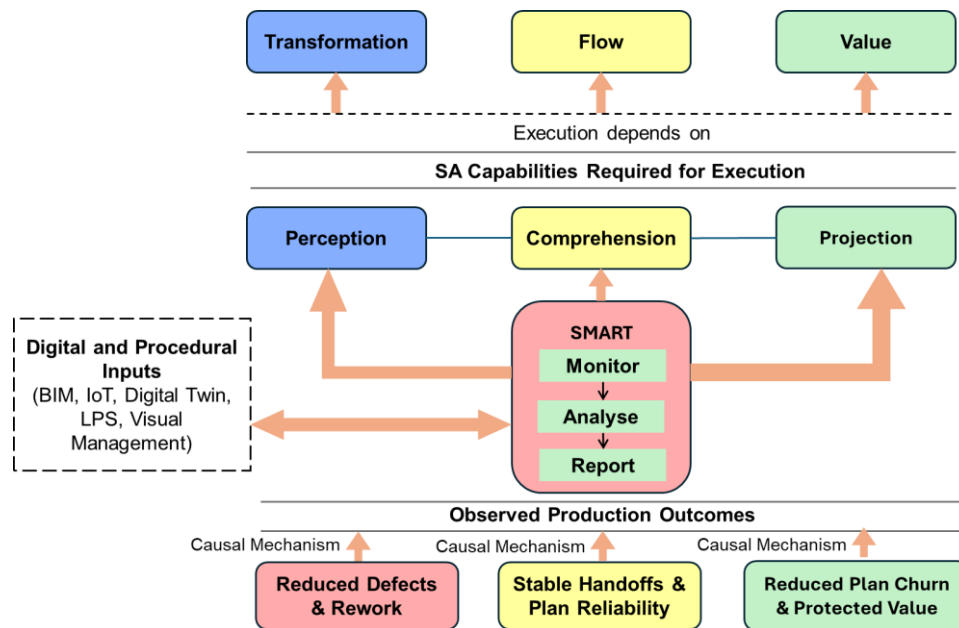


Figure 2: Conceptual model showing how SMART operationalises SA (perception, comprehension, projection) to enable the realisation of TFM objectives defined by TFM.

### SA AS AN ENABLER

Figure 2 depicts SA in terms of Endsley's SA model, which includes perception, comprehension, and projection. Each capacity pertains to production control but does not have a strict one-to-one mapping to TFM. Perception enables correct recognition of field conditions, supporting more reliable execution of transformation activities. Comprehension connects conditions to actors and work packages; mismatch can contribute to unsteady flow and coordination breakdowns. Projection focuses on how existing conditions evolve, which helps to protect value by allowing for the prediction of downstream consequences. Rather than deterministic mapping, Figure 2 depicts them as propositions: varied SA capacities affect diverse TFM goals in practice. This is based on the insight that transformation relies on correct representation, flow on shared understanding of limitations and interdependencies, and value on predicting downstream impacts at the decision-making stage.

### SMART AS AN OPERATIONAL BRIDGE

While digital technologies and lean procedures create data, signals, and cues, these do not, by themselves produce shared SA. In this regard, SMART is positioned as the operational mechanism through which SA is created and aligned, as shown in Figure 2. SMART is positioned between the digital and the procedural inputs and the SA layer, highlighting its mediating role. SMART addresses the gap in the lean tools and procedures through a monitor-analyse-report cycle. Monitoring brings together all the relevant signals and field observations to improve perception. Analysis supports the collective interpretation of constraints and dependencies, enabling shared comprehension. Reporting translates these interpreted cues into concise, role-specific narratives that support projection by making near-term implications at decision points. SMART supports all three SA capacities rather than targeting a single TFM objective. This reflects the argument that stabilising SA is a system requirement for TFM-based planning and control.

### MECHANISMS AND AN ABDUCTIVE CASE EXAMPLE

This section specifies the mechanisms through which SMART-enabled SA operationalises TFM in construction production.

## MECHANISMS LINKING SMART TO TFV OUTCOMES

The proposed mechanism explains how SA is generated, aligned through SMART while allowing the realisation of TFV objectives objectives under uncertainty.

**Transformation Mechanism:** Transformation performance is dependent on the timely and accurate perception of field conditions. When perception is delayed or skewed, work is released with inaccurate assumptions, resulting in more specification-reality mismatches. SMART increases perception by enhancing monitoring and validation of field cues before commitment, lowering execution errors, rework, and task duration variability. This works at the work-package level, without changing task logic or methods. It can be measured using metrics such as the proportion of limitations detected before execution and reductions in first-pass faults or rework. Therefore, this paper recommends the following:

- **P1:** Higher accuracy and timeliness of situational perception at the point of work release is expected to be associated with lower rework and higher first-pass task completion, observable through improved constraint identification prior to execution. These indicators can be assessed using standard Lean project records such as constraint logs, PPC trends, and rework tracking.

**Flow Mechanism:** Flow is less dependent on local task execution and more on a shared understanding of limitations and interdependencies among roles. Fragmented interpretations reduce visibility and lead time, while increasing interface variability. SMART employs structured analysis to align judgements about what constraints work and why. This increases constraint visibility and advance notice, decreases handoff variability, and boosts plan reliability measures like PPC and takt adherence.

It does not eliminate uncertainty. It transitions from reactive to anticipatory. Better alignment in constraint interpretation leads to improvements in PPC, takt adherence, and plan stability. Based on this, the study suggests the following:

- **P2:** Greater cross-role alignment in the comprehension of constraints and dependencies is expected to be associated with improved handoff and higher plan reliability, observable through increased PPC and reduced plan variability.

**Value Mechanism:** Value delivery under uncertainty necessitates short-term projection rather than long-term optimisation. When the short-term repercussions of decisions are not expressly foreseen, resequencing and buffering occur later, typically at the expense of client-valued results. SMART-supported reporting is positioned to make short-term estimates explicit at decision points, allowing for rapid resequencing and buffer insertion. This minimises downstream disruptions and protects value even when they do occur. This can be observed through explicit identification of downstream impacts and reductions in plan churn and late-stage resequencing. In this regard, this work proposes the following:

- **P3:** Explicit short-horizon projection of downstream impacts during planning and commitment is expected to be associated with reduced plan churn and improved protection of client-valued outcomes, observable through reduced late resequencing and improved plan stability.

**Feedback Mechanism:** The recurring Monitor-Analyse-Report cycle creates a feedback loop between plans and field conditions. Each cycle changes the shared situational model on which subsequent decisions are based. Over time, this strengthens the link between intent and execution, allowing for learning across planning cycles. Importantly, this feedback relies on awareness alignment rather than extra control constraints. This can be observed through reduced recurrence of similar constraints and improved stability across planning cycles. In this regard, this work proposes the following:

- **P4:** Regular Monitor-Analyse-Report cycles are expected to be associated with improved alignment between plans and field conditions over time, observable through reduced recurrence of similar constraints across planning cycles.

### **CASE ILLUSTRATION: SMART IN A TFF FAILURE CONTEXT**

Multiple studies document that, despite active engagement with TFF-based routines such as lookahead planning, constraint analysis, and weekly commitment management in the Last Planner System, projects frequently experience late constraint discovery, inconsistent handoffs, frequent plan adjustments, and limited or unreliable gains in PPC (Hamzeh et al., 2012; Tommelein, 2015).

A case-based illustration from the previous published SMART application highlights how such failures manifest and are addressed in practice (Sahadevan et al., 2025). In a modular construction project, SMART identified delays in completing corridor slabs and staircase installation that were outside the primary subcontractor's scope. While existing Lean routines captured the delay as a deviation from plan, SMART combined site observations, digital records, and interviews with site personnel to identify the underlying cause: fragmented responsibilities across multiple agencies and misaligned assumptions about task readiness. SMART broadcast integrated interview insights and site observations to show that the delay was driven by interdependent work outside the subcontractor's scope, requiring coordination across agencies. This reframed the issue from a task delay to a coordination problem, leading to reassessment of responsibilities and sequencing before subsequent planning commitments.

## **DISCUSSION AND CONCLUSIONS**

This work examined the persistent underperformance of TFF-based planning and control in construction projects operating under uncertainty (Hamzeh et al., 2012; Tommelein, 2015). The core finding is that TFF implicitly assumes aligned SA at the point of decision-making, an assumption that is frequently violated in practice. By introducing SMART as a socio-technical mechanism, the paper operationalises how SA can be generated and aligned, thereby improving decision quality within TFF-based planning and control under dynamic conditions.

Prior lean literature has documented the late constraint discovery, unstable plan reliability, and repeated resequencing despite the use of TFF-based routines (Ballard & Tommelein, 2021; Hamzeh et al., 2012). These outcomes are typically attributed to incomplete constraint removal, weak commitment discipline, or inherent variability (Tommelein, 2015). This work reframes these outcomes by shifting the attention from procedural adequacy to the quality and the alignment of situational understanding at the decision points. Rather than treating SA as an implicit background condition, this paper makes it explicit as a limiting factor in TFF-based planning and control. In contrast to the digital construction literature, which often frames coordination problems such as data availability or integration issues (Reinbold et al., 2019; Sacks et al., 2020), the analysis shows that increased perception alone does not ensure shared SA. This explains why SA when unmanaged, remains incomplete and uneven across roles, leading to inconsistent and unreliable outcomes. Similarly, procedural aspects of lean assume a coherent situational picture without specifying how it is produced. SMART is positioned as an explanatory layer. It connects observed TFF failures to misalignment in SA during decision-making. It explains why lean practices yield divergent outcomes across projects.

Theoretically, this work complements TFF by articulating informational and cognitive preconditions required for its execution, contributing to a mechanism-level explanation of lean production theory under uncertainty. This work does not extend TFF as a production theory but specifies the informational and situational conditions required for its application in production planning and control. It reframes TFF underperformance as a SA problem rather than a tools or principles problem. Although SA has recently been explicitly explored in lean

contexts, especially in takt production and digital visual management, these studies are still primarily concerned with worker-level awareness, real-time data streams, or waste visualisation rather than a production-integrated mechanism for shared SA at lean decision points (Görsch et al., 2025; Halttula & Seppänen, 2022). Practically, these findings suggest that improving lean performance may depend less on adding new planning artefacts and more on structuring how existing signals or observations are interpreted and communicated within existing routines (Görsch et al., 2020, 2025). SMART contributes by generating causal explanations of deviations, validates constraint status and provides short-horizon projections that can be included into lookahead, make-ready, and weekly planning cycles, shifting decision-making from plan compliance tracking to explaining what occurred, why deviations arose, and how actions should be adjusted.

The limitations of the work are as follows: the paper is conceptual and relies on abductive reasoning based on the existing literature. While the proposed SMART concept has been tested in construction contexts previously, these were not under a lean project context (Prabhu & Singh, 2024; Sahadevan et al., 2025). Furthermore, the propositions presented here are not tested in the lean Takt contexts. Accordingly, the analysis does not establish causal effects or claim generalisability. Furthermore, the different measurement methods of SA have their own limitations and accordingly this research highlights proxy indicators as a measure of SA.

Future research should empirically test SA as a mediating production condition within Takt-based production planning and control. This requires operationalising SA into measurable constructs. Empirical designs should include embedded case studies at lookahead and weekly planning levels, quasi-experiments comparing projects with and without structured SA routines, and longitudinal studies tracking constraint recurrence and plan–field alignment. Future work should define boundary conditions and refine the SMART mechanism. The effects of SA likely vary with project complexity, uncertainty, interdependence and Lean maturity. Comparative studies across project types and delivery systems are needed. Operational research should specify SMART cadence within planning cycles, standardise reporting artefacts, and assess implementation cost and feasibility. Controlled comparisons of alternative configurations can clarify scalability. Theoretically, SA should be more tightly linked to the “status of the system” in pull production and to resilience constructs such as monitoring and anticipation, to position it as a testable component within production theory.

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