

A Theoretical Mathematical Model for Identifying Critical Success Factors in the Digital Transformation of Medical Laboratory Services

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Abstract. *Most healthcare services and specifically, laboratory organizations focus the discourse of digitalization processes primarily as technological vehicles and limit managerial approaches & process mechanisms limiting success. Previous research emphasizes the importance of digital technologies for efficiency enhancement and data availability but often considers critical success factors in isolation and without an explicit formalization of interdependencies. Consequently, the judgement of digital transformation effects continues to be conceptually uniform and impossible to analyse comparatively accross organisational contexts. This article presents a theoretical mathematical model that aims to identify and structure the critical success factors of digital transformation in medical laboratory services. The methodology used is formal and conceptual, since it defines the key constructs, evaluation criteria, and functional relationships without seeking empirical testing at this stage. Within this field, we read success in digital transformation as a kind of managerial and process performance that arises from the alignment between how technological features manifest in operational processes and decision-making mechanisms. The framework that is developed in this study incorporates four core dimensions: strategic alignment, process controllability, performance indicator use as decision-support tools and technological investment. We operationalize these dimensions through normalized composite variables and then aggregate them together using alternative linear and multiplicative functional forms to generate multiple compensatory or non-compensatory assessments of digital transformation success. The model encourages focusing on process stability and quality of service while making data-driven managerial decisions instead of treating technology as an end-all determinant. The major addition of this paper is offering a consistent mathematical-oriented conceptual framework that allows the systematic evaluation on maturity of the digital transformation for medical laboratory services. The proposed model can serve as a useful basis for conducting future empirical studies, comparative assessments and the design of decision-support tools in regulated and quality-critical healthcare settings.*

Keywords: digital transformation, medical laboratory services, quality management, process controllability, decision-support indicators.

Introduction

The digital transformation of healthcare services is a complicated process, and any one part of this process has the potential to affected the quality, safety and efficiency of medical care delivery. The academic literature stresses that digitalization alone does not enhance organizational performance, but rather begets positive or negative outcomes conditional to how digital technologies are combined with organizations structures and decision making processes (Vial, 2019; Verhoef et al., 2021).

In the case of medical laboratory services, this complexity is further intensified by a strong dependence on the stability of operational processes, data traceability, and the need to comply with strict quality and regulatory requirements. Prior studies highlight the critical role of laboratory information systems (LIS) and automation; however, they predominantly approach digitalization as a technological endeavor, focusing on system implementation and interoperability, while insufficiently analyzing the managerial mechanisms through which these technologies influence organizational performance (Mencacci et al., 2023; Hawkins, 2007).

A significant portion of the literature adopts a fragmented empirical approach, relying on case studies or survey-based research to identify isolated success factors (such as leadership, digital competencies, or IT infrastructure), without integrating them into a coherent conceptual or mathematical framework (Kane et al., 2015; Matt et al., 2015). While these studies provide valuable descriptive insights, they limit generalizability and do not allow for a systemic evaluation of the interdependencies among factors.

Furthermore, recent research on digital transformation in healthcare points to a conceptual ambiguity between digitization, digitalization, and digital transformation, leading to the use of heterogeneous indicators and difficulties in comparing results across studies (Reis et al., 2018). The lack of mathematical formalization makes it challenging to quantify the relationships between technological investments, operational processes, and managerial decision-making.

The underestimation of the role of quality management and related performance indicators its another major limitation of the literature. Although concepts such as data-driven decision-making and quality improvement are frequently referenced, they are rarely integrated into a formal model that explicitly demonstrates how process, outcome, and perception indicators contribute to the success of digital transformation initiatives (Kaplan & Norton, 1996; Porter & Teisberg, 2006).

The rest of the paper contributes to the formalisation of relationships between strategic alignment and process controllability, how indicators are treated as decision-support tools and how this fits into technological investments, combined within a single mathematical framework that preserves both process-related (inherent in medical laboratory) and managerial specificities. This analytical framework proposes a rigorous conceptual foundation for assessing digital transformation success and provides the groundwork upon which future comparable, reproducible empirical validations may be developed.

Theoretical research hypothesis

The success of digital transformation in medical laboratory services is predominantly determined by organizational and managerial factors that ensure the effective integration of digital technologies into decision-making processes and quality management, rather than by the level of technological investments per se.

Methodology

The primary objective of the present study is proposing the development of a mathematical framework for identifying the critical success factors of digital transformation in medical laboratory services. The research focuses on defining the relevant concepts, evaluation criteria, and functional relationships, without pursuing empirical validation of the model at this stage.

The methodological objective of the study is to develop an integrative mathematical model. The model should be capable of capturing the interdependencies between strategic alignment, process controllability, the use of indicators as decision-support tools, and technological investments, in a manner consistent with quality management system practices in medical laboratory services.

Although the study does not include an empirical application, the proposed methodological framework is constructed to allow subsequent use and validation in future research. In this article, the paper explicitly distinguishes between the stage of theoretical formalization and the subsequent stages of empirical testing and calibration, which may be undertaken in future studies.

The selection of medical laboratory services as the application domain is motivated by their specific process and organizational characteristics, which include a strong dependence on stable processes, reliable data, and managerial decisions grounded in performance and quality indicators. These characteristics make laboratory activities a suitable context for the development and application of a rigorous mathematical framework for analyzing digital transformation.

Defining the concept of digital transformation success in medical laboratory services

Measuring the success of a digital transformation initiative can be done by evaluating its impact on how an organization operates. Especially in relation to the organization maintaining control and stabilization of processes, ensuring quality service delivery, and anchoring managerial decisions with data-backed, relevant and correlated indicators. We can now define success in the context of digital transformation as making it easier for firms to be more predictable and less variable in their operations, thereby improving decision quality.

Digital transformation success is assessed through its effects on organizational functioning. Particularly with regard to the organization's ability to control and stabilize processes, ensure the quality of delivered services, and ground managerial decisions in relevant and correlated indicators. From this perspective, digital transformation is considered successful so far as it contributes to increased predictability, reduced operational variability, and improved quality of managerial decision-making.

The digital transformation success in laboratory industry is defined through four fundamental dimensions: process stability, operational controllability, service quality, and managerial decision quality.

Process stability refers to maintaining controlled variability in operational workflows, particularly in relation to turnaround times, sample reprocessing or rejection rates, and compliance with result delivery deadlines.

The laboratory's capacity to monitor processes and mediate in a timely manner, based on the information provided by digital systems is defined as operational controllability.

Service quality is understood in a broad sense, encompassing both the accuracy and reliability of laboratory results and compliance with regulatory requirements and applicable quality standards.

Quality managerial decision reflects the extent to which decisions are grounded in consistent data derived from process, outcome, and perception indicators, used in an integrated manner.

Within this framework, digital transformation success presupposes the existence of an indicator system capable of preventing local optimizations and supporting a systemic view of organizational performance.

The definition of digital transformation success is closely linked to the structure of laboratory activities organized along the pre-analytical–analytical–post-analytical chain. The present study considers digital transformation to be truly successful when digital solutions contribute to the coherence and continuity of this chain, facilitating traceability, error reduction, and coordinated decision-making at the organizational level.

This conceptualization of digital transformation success provides the foundation for defining the constructs and evaluation criteria employed in the mathematical model presented in the following section.

Figure 1 conceptually illustrates digital transformation success as the result of integrating digital technologies into laboratory processes and managerial decision-making, highlighting the role of process stability and controllability, service quality, and managerial decision quality within the pre-analytical–analytical–post-analytical chain. It depicts the complete laboratory examination process, including stages from test request and sample collection/transport to measurement (under quality control), validation, reporting, communication of critical results, and turnaround time monitoring. The chain-based approach enables the identification of vulnerable points and the implementation of improvement measures oriented toward patient safety.

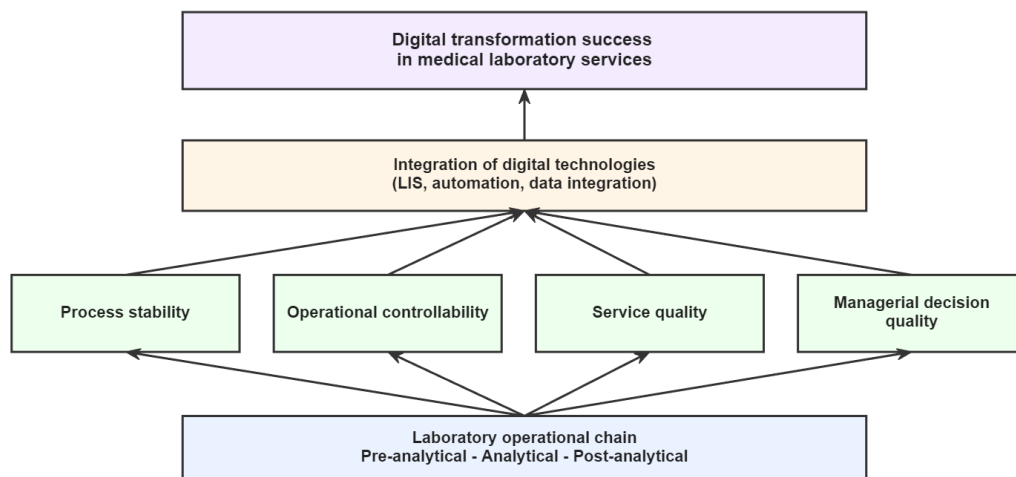


Figure 1. Conceptual dimensions of digital transformation success in medical laboratory services

Source: authors' own research contribution.

Defining the constructs and evaluation criteria

To build a mathematical model that can meaningfully describe digital transformation in medical laboratory services, the first step is to clarify the constructs and the evaluation criteria that give shape to the conceptual dimensions defined earlier. In practice, these constructs represent the managerial and organizational aspects that influence how digital transformation unfolds, while the evaluation criteria translate those aspects into measurable elements that reflect the realities of

laboratory operations. By defining both clearly, the model can move from abstract ideas to variables that can be analyzed, compared, and eventually used to assess performance.

The four fundamental constructs are: strategic alignment, process controllability, the use of indicators as decision-support tools, and technological investments. These constructs are selected to capture the mechanisms through which digital transformation influences organizational performance, avoiding a reduction of success to an exclusively technological perspective.

In the context of medical laboratory services, strategic alignment describes the degree to which digital transformation initiatives are genuinely connected to the laboratory's overall direction and everyday priorities. In practice, this means more than simply having a digital strategy written on paper. It involves ensuring that the goals of digitalization are understood across the organization, that they support quality improvement and regulatory expectations, and that they are realistically integrated into routine activities.

From a managerial perspective, this alignment becomes visible when senior leaders participate directly in decisions about digital tools, when digital objectives are included in operational discussions, and when budget planning reflects the laboratory's long-term digital needs rather than short-term fixes.

This aspect is particularly important in medical laboratories because, without a shared vision, digitalization tends to happen in fragments. Different departments may adopt isolated tools, or individual processes may be optimized locally without improving the overall workflow. Over time, this can lead to a patchwork of unrelated systems that complicate work instead of supporting it, ultimately weakening process stability and reducing the quality of managerial decisions.

Process controllability refers to the laboratory's ability to monitor, control, and stabilize operational processes across the entire pre-analytical–analytical–post-analytical chain. Evaluation criteria include the level of process standardization, the capability for real-time monitoring, the ability to identify and correct deviations, and the stability of operational indicators over time.

Process controllability is a critical determinant of service quality and safety in the domain of healthcare. From a managerial perspective, this construct reflects the extent to which digital transformation enables a shift from reactive control to anticipatory control, based on data and relevant operational indicators.

The use of indicators as decision-support tools is defined as the extent to which process, outcome, and perception indicators are systematically and integratively employed in managerial decision-making processes. The associated criteria address the relevance of indicators for decision-making, data coherence and quality, the correlation among indicators, and the ability to avoid local optimizations through integrated analysis.

This construct is central to medical laboratory services, where managerial decisions directly affect process stability and the quality of delivered results. Effective use of indicators reflects organizational maturity and the capability to translate data generated by digital systems into well-founded managerial actions.

Technological investments are defined as the resources allocated to IT infrastructure, automation, and digital solutions, relative to the size and complexity of the laboratory. Evaluation criteria include the level of investment, the degree of digital coverage of processes, and the currency of implemented solutions.

Capital allocated to digital tools is considered a necessary factor, but it is important to mention that it isn't a sufficient factor for digital transformation success. The relevance of this

construct lies in assessing its relative role in relation to organizational and managerial factors, allowing a clear distinction between digitalization and actual performance.

The four constructs are not treated as independent dimensions, but as interrelated elements connected through managerial decision-making mechanisms. Strategic alignment sets the direction of digital transformation, process controllability reflects execution capability, decision-support indicators underpin managerial decision-making, and technological investments provide the necessary infrastructure. Together, these constructs define the framework within which digital transformation success can be coherently evaluated and quantified.

This definition of constructs and evaluation criteria provides the basis for the operationalization of variables and for the mathematical formalization of the model, presented in the following section.

Figure 2 illustrates the conceptual relationships between strategic alignment, process controllability, the use of indicators as decision-support tools, and technological investments, highlighting their role in supporting digital transformation success in medical laboratory services. The relationships presented are conceptual in nature and precede the mathematical formalization of the model.

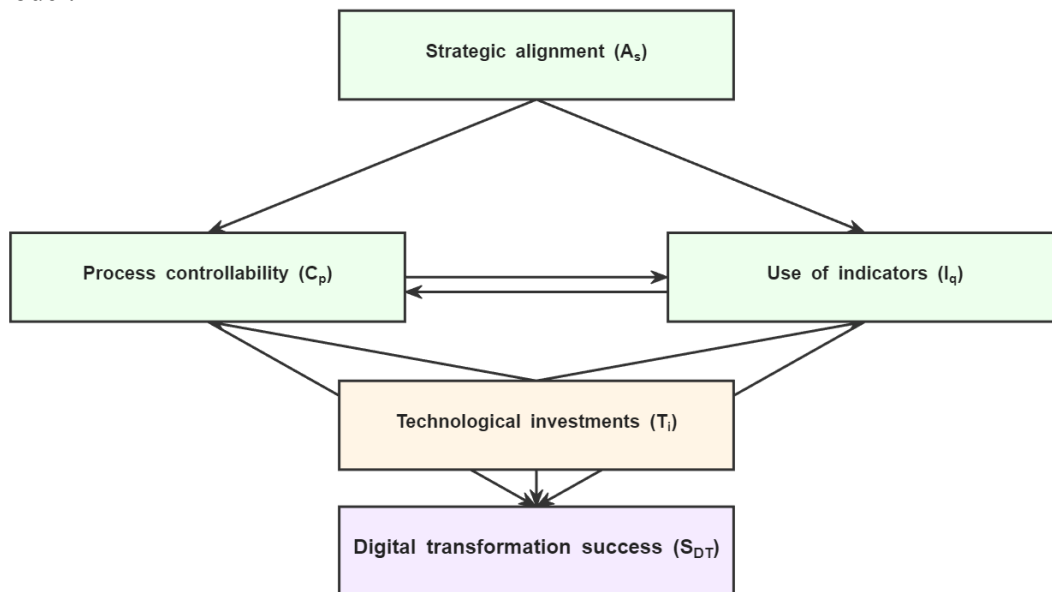


Figure 2. Conceptual relationships between the constructs used in the digital transformation success evaluation model

Source: authors' own research contribution.

Operationalization of variables and indicators

Operationalization aims to ensure coherence between the conceptual and mathematical levels, as well as to obtain variables that are interpretable from a managerial perspective and adapted to the specific characteristics of medical laboratory services.

The model includes four explanatory variables: strategic alignment (A_s), process controllability (C_p), the use of indicators as decision-support tools (I_q), and technological investments (T_i). Each variable is constructed as a composite indicator, resulting from the aggregation of a set of elementary indicators defined according to the nature of laboratory-specific processes and decision-making activities.

The operationalization of variables is based on a classification of indicators into three complementary categories: process indicators, which reflect the stability and control of operational workflows (e.g., turnaround times, reprocessing rates, process variability); outcome indicators, which capture the effects of digital transformation on service performance and quality (e.g., error reduction, resource utilization efficiency, compliance with standards); perception indicators, which reflect the subjective assessments of the involved stakeholders (e.g., staff perceptions of the usefulness of digital systems, beneficiary satisfaction).

This structure enables the capture of both objective and managerial dimensions of digital transformation success.

Each variable $X \in \{A_s, C_p, I_q, T_i\}$ is defined as a weighted aggregation of a set of n_X elementary indicators x_i :

$$X = \sum_{i=1}^{n_X} w_i \cdot x_i$$

where: x_i represents the elementary indicator corresponding to variable X ; w_i denotes the weight associated with indicator x_i , subject to the condition:

$$\sum_{i=1}^{n_X} w_i = 1, w_i \geq 0$$

This formulation ensures the comparability of variables and allows their interpretation as aggregated performance scores.

To avoid distortions caused by different measurement units and to enable coherent aggregation of indicators, all elementary indicators are normalized to the $[0,1]$ interval using the min-max normalization method:

$$x_i^* = \frac{x_i - x_i^{\min}}{x_i^{\max} - x_i^{\min}}$$

where: x_i represents the current value of the indicator; $x_i^{\min}$ and $x_i^{\max}$ denote the minimum and maximum admissible or observed values.

In the case of negatively oriented indicators (e.g., time-based measures or error rates), the scaling is inverted so that higher values of the normalized indicators reflect superior performance.

The aggregation of elementary indicators is performed using a weighted average, chosen for its interpretability and compatibility with managerial decision-making. This choice avoids unnecessary complexity associated with nonlinear functions at the theoretical formalization stage and enables the direct identification of each dimension's contribution to the final score.

For the variables A_s , C_p and I_q aggregation emphasizes internal coherence and the avoidance of excessive compensation among indicators, whereas for T_i aggregation primarily reflects the relative level of available technological support.

The weights w_i used in indicator aggregation are defined normatively, based on expert judgment in the field of medical laboratory services. This approach is justified by the fact that the relative importance of indicators cannot be determined exclusively through statistical methods in the absence of empirical validation, and that the specific characteristics of the domain require a qualitative assessment of indicator relevance.

Some dimensions in the structure of medical laboratory services contrast with others (the characteristic that represents process stability and quality must be relevant) as opposed to absolute levels of technological investments. This managerial reality can be expressed in the mathematical model through normative weights, which provide ties with internal quality control.

The weights are defined as tunable variables that can be re-tuned from one experiment to another without modifying the model's architecture.

Formalization of the integrative mathematical model

The mathematical model aims to synthesize these dimensions into a composite, interpretable, and comparable indicator that can be used to assess the maturity of digital transformation at the organizational level.

Digital transformation success is defined as a function of four variables, as follows:

$$S_{DT} = f(A_s, C_p, I_q, T_i)$$

where: S_{DT} represents the overall score of digital transformation success; A_s denotes strategic alignment; C_p reflects the controllability of operational processes; I_q captures the use of indicators as decision-support tools; T_i represents the level of technological investments.

This general formulation allows flexibility in the choice of the functional form and ensures the model's compatibility with different organizational contexts and levels of digital maturity.

A first formal expression, suitable for comparative evaluations and maturity analyses, is the weighted linear form:

$$S_{DT} = \alpha A_s + \beta C_p + \gamma I_q + \delta T_i$$

where: the coefficients $\alpha, \beta, \gamma, \delta \geq 0$ represent the weights associated with each variable, subject to the condition $\alpha + \beta + \gamma + \delta = 1$.

This form allows the direct interpretation of the relative contribution of each dimension to digital transformation success and is compatible with the use of the normative weights defined previously.

Alternatively, the model can be extended to capture complementarity relationships or limiting effects by using nonlinear functional forms of a multiplicative type, such as:

$$S_{DT} = A_s^\alpha \cdot C_p^\beta \cdot I_q^\gamma \cdot T_i^\delta$$

This formulation penalizes major imbalances between dimensions and reflects the assumption that very low levels of one variable may constrain the overall success of digital transformation, regardless of high values of the others.

The model coefficients have a direct managerial interpretation. Higher values of the coefficients α , β , and γ reflect the importance of organizational and managerial factors relative to the strictly technological component δ .

In the context of medical laboratory services, this structure aligns with the hypothesis that digital transformation success is predominantly driven by the integration of technology into decision-making processes and quality management, rather than by the level of IT investments per se.

The coefficients may be defined normatively, based on domain expertise, or subsequently calibrated using empirical methods, without modifying the core structure of the model.

To enable the use of the model in comparative analyses across organizations or in longitudinal evaluations, several essential methodological conditions must be met: all variables A_s, C_p, I_q, T_i must be normalized on the same interval; the structure of elementary indicators and their associated weights must be kept constant across the organizations being compared; the interpretation of S_{DT} values must be carried out in relation to the operational and regulatory context specific to medical laboratory services.

Under these conditions, the model enables the comparison of the relative level of digital transformation success across similar organizations, the identification of strengths and structural

imbalances, and the substantiation of strategic decisions regarding the prioritization of digital transformation initiatives.

Theoretical criteria for model validity, consistency, and robustness

Since the study is primarily theoretical and has not yet being empirically validated at this stage, the model is assessed against a number of theoretical criteria for validity, consistency and robustness in order to establish the methodological rigour and practical relevance of the mathematical framework. These criteria are designed to show how coherent the model is and how consistent it is with the managerial specifics of medical laboratory services.

A primary criterion of validity is the internal coherence of the constructs used in the model. Each explanatory variable (A_s, C_p, I_q, T_i) is distinctly defined, without conceptual overlap, and the relationships among them are explicitly delineated within the conceptual framework presented earlier. The constructs are derived directly from the dimensions of digital transformation success defined in Section “Defining the concept of digital transformation success in medical laboratory services” and are aligned with the managerial and operational roles specific to laboratory activities. This conceptual coherence ensures that the model measures a unified phenomenon and avoids the ambiguities frequently encountered in the digital transformation literature.

The model is designed to prevent the phenomenon of local optimizations, whereby improvements in a single dimension (e.g., technological investments) are erroneously interpreted as overall digital transformation success. Both the weighted linear form and the multiplicative form of the S_{DT} function simultaneously integrate all relevant factors, penalizing major imbalances among dimensions.

In particular, the use of a multiplicative form highlights the systemic nature of digital transformation, in which deficiencies in one dimension may constrain overall performance, regardless of the levels of the others.

Another essential robustness criterion is the stability of the model’s results under moderate variations of elementary indicators or normative weights. The adopted aggregation structure and the normalization of variables to a common interval reduce excessive sensitivity of the S_{DT} score to point fluctuations.

In this way, the model is suitable for comparative evaluations and longitudinal analyses, without generating artificial variations in results due to marginal changes in input data.

The criterion of managerial interpretability, is essential for practical applicability of the model. Each variable and each coefficient has a clear meaning from a managerial decision-making perspective, and the aggregated result S_{DT} can be used as a diagnostic tool for assessing digital transformation maturity.

This interpretability allows medical laboratory management to identify not only the overall level of digital performance, but also the structural sources of potential imbalances.

Lastly, the model incorporates elements of quality management systems applicable to medical laboratory services. Its process and outcome indicator-oriented design, together with the focus on using data for managerial decision-making is consistent with existing quality-focused frameworks. This compatibility allows model implementation in current organizational assessments and is supportive of the model's utilization as a complementary intervention in performance and quality management.

Use of the model and future validation perspectives

Areas of managerial decisions where the model can be applied include (but are not limited to): selecting digital transformation initiatives based on structural imbalance; evaluating how various technological investments will affect process-related and decision-related performance; longitudinal tracking of a firm's digital maturity rate over time; pinpointing functional areas needing intervention or serious attention at a specific moment in time.

By coherently aggregating strategic, process-related, and technological dimensions, the model supports a systemic approach to digital transformation, avoiding fragmented interpretations of performance.

The empirical application of the model requires the collection of a structured dataset corresponding to the indicators defined previously. These include the following types of data: operational data derived from laboratory information systems (e.g., turnaround times, reprocessing rates, workflow stability); managerial data related to strategies, internal policies, and the use of indicators in decision-making processes; perception data obtained from staff assessments and, where applicable, from service beneficiaries.

This diversity of data enables robust testing of the model and calibration of the weights used in variable aggregation.

Empirical validation of the model may be conducted through cross-sectional or longitudinal studies applied to samples drawn from comparable medical laboratories. Validation directions include testing the relationships between explanatory variables and organizational performance, analyzing the sensitivity of the model to variations in weights, and assessing its predictive capability over time. Such studies may contribute to refining the model structure and adapting it to different organizational contexts.

We also have a foundation for future extents, such as the incorporation of advanced data analysis techniques and artificial intelligence to detect performance patterns or anticipate developments of digital maturity.

The formulated mathematical basis can also be employed to build benchmarking instruments between organizations or simulate the consequences of various digital transformation approaches.

By following these pathways of application and validation, the model is offered as a natural and extensible framework that can provide support for both academic research and managerial practice in the domain of medical laboratory services.

Results

The results presented in this section are not empirical in nature; rather, they aim to highlight the structural properties of the S_{DT} function, the relationships among the explanatory variables, and the managerial implications arising from the mathematical form of the model.

Given the normalization of the explanatory variables, $C_p, I_q, T_i \in [0,1]$, the digital transformation success score is defined on the same interval:

$$0 \leq S_{DT} \leq 1$$

The model is analyzed using two complementary functional forms. The first is the weighted linear form, which is an affine function that is monotonically increasing with respect to each variable. It is characterized by a high degree of managerial interpretability and by a compensatory aggregation mechanism:

$$S_{DT} = \alpha A_s + \beta C_p + \gamma I_q + \delta T_i, \quad \text{with } \alpha + \beta + \gamma + \delta = 1$$

The second is the weighted multiplicative form, which introduces a non-compensatory mechanism by explicitly penalizing major imbalances among dimensions. The two forms reflect different evaluation logics: one suitable for aggregated maturity analyses, and the other for contexts in which certain dimensions constitute critical constraints related to quality and compliance:

$$S_{DT} = A_s^\alpha \cdot C_p^\beta \cdot I_q^\gamma \cdot T_i^\delta$$

To illustrate the behavior of the model, hypothetical numerical scenarios are employed, constructed using values considered plausible for medical laboratories at different levels of digital maturity. The scenarios reflect situations such as predominantly technology-driven digitalization, strong managerial integration, process-related imbalances, and high digital maturity.

The values are expressed on the normalized [0,1] scale, and the weights α , β , γ , and δ are defined normatively for illustrative purposes. The objective of these scenarios is not empirical calibration of the model, but rather the highlighting of structural differences between the functional forms and among the organizational configurations analyzed.

To enable a direct comparison between the two forms of the model, the analysis focuses on the variation of the S_{DT} score as a function of operational process controllability (C_p), while keeping the other variables (A_s , I_q , T_i) constant at the values corresponding to each scenario.

Figure 3 presents the theoretical variation of the S_{DT} score as a function of C_p for the weighted linear form. The resulting relationship is linear, with a constant slope, reflecting the compensatory nature of the aggregation mechanism. High levels of strategic alignment, indicator use, or technological investments can partially mitigate the effects of a low level of process controllability.

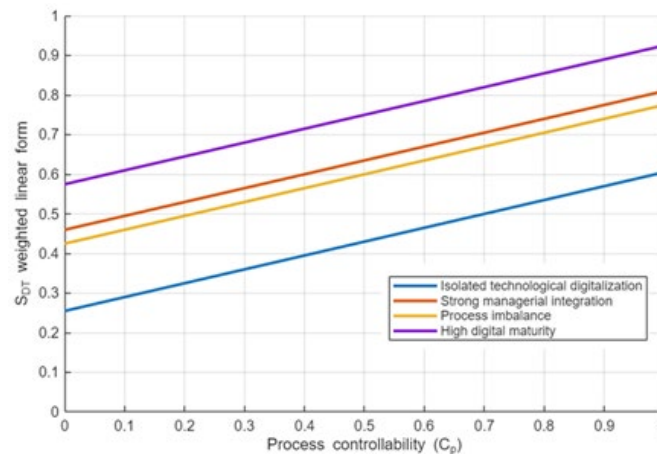


Figure 3. Theoretical sensitivity of the digital transformation success score (S_{DT}) to variations in process controllability (C_p) in the weighted linear form of the model

Source: authors' own research contribution.

Figure 4 presents the same analysis for the weighted multiplicative form. In this case, the relationship between S_{DT} and C_p becomes nonlinear, and low levels of process controllability lead to significant reductions in the overall score, even in scenarios characterized by high levels of the other dimensions. This behavior highlights the existence of critical bottleneck effects, typical of contexts in which process stability represents a critical performance condition.

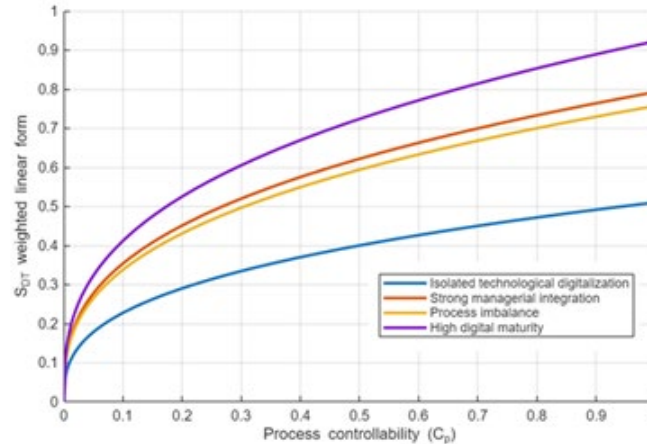


Figure 4. Theoretical sensitivity of the digital transformation success score (S_{DT}) to variations in process controllability (C_p) in the weighted multiplicative form of the model

Source: authors' own research contribution.

For the linear form of the model, the marginal sensitivity of the S_{DT} score with respect to each explanatory variable is given directly by the associated coefficient:

$$\frac{\partial S_{DT}}{\partial A_s} = \alpha, \quad \frac{\partial S_{DT}}{\partial C_p} = \beta, \quad \frac{\partial S_{DT}}{\partial I_q} = \gamma, \quad \frac{\partial S_{DT}}{\partial T_i} = \delta$$

This property confers a high degree of managerial interpretability to the model, as the coefficients can be interpreted as constant marginal effects of each dimension on the overall outcome.

Figure 5 provides a visual representation of these marginal effects, highlighting the relative importance of each variable within the normative weighting scheme employed.

The relationship $\beta > \delta$, explicitly illustrated in the figure, indicates that a marginal increase in process controllability has a greater impact on digital transformation success than a similar increase in the level of technological investments. From a managerial perspective, this result suggests that allocating resources toward stabilizing and controlling operational processes yields more consistent benefits than isolated increases in IT budgets, particularly in the context of medical laboratory services.

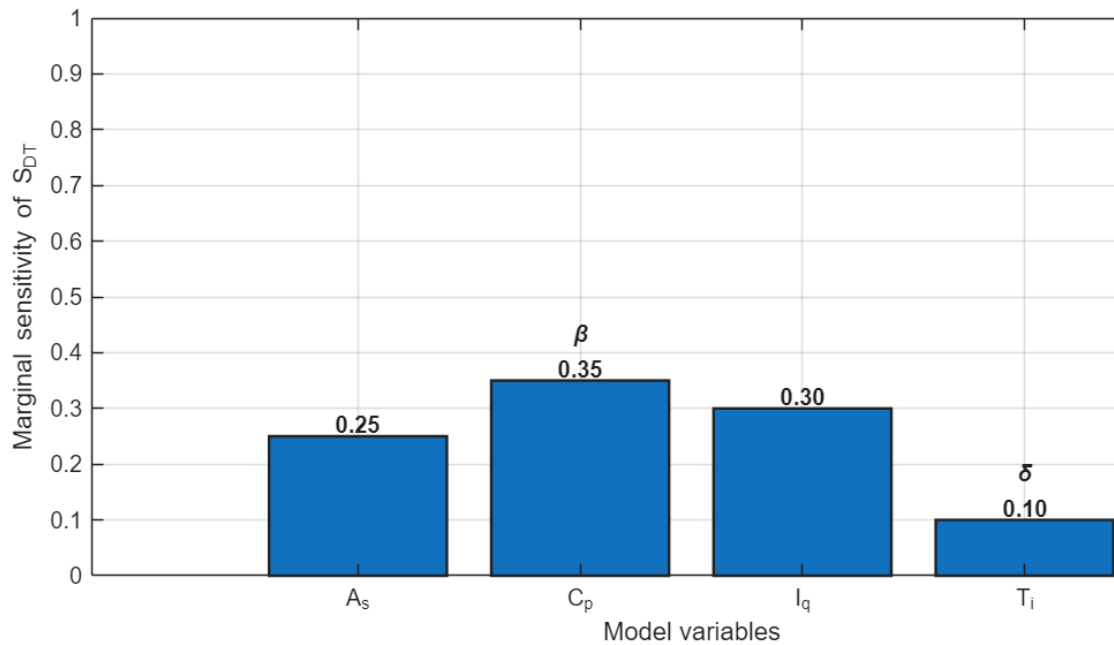


Figure 5. Marginal sensitivity of the digital transformation success score (S_{DT}) with respect to the explanatory variables in the linear form of the model

Source: authors' own research contribution.

The theoretical analysis indicates that success in digital transformation is not a straightforward maximization of one dimension, but rather depends on the structural interplay among organizational, process and technological factors. The linear form of the model is suitable for aggregated evaluations and general maturity comparisons, whereas the multiplicative form is more appropriate for contexts in which explicit penalization of imbalances and the identification of dimensions critical to quality and compliance are required.

Discussions

The results of the theoretical analysis of the mathematical model allow for a coherent interpretation of the structural relationships among the factors that determine digital transformation success in medical laboratory services. By employing two complementary functional forms and illustrative graphical representations (Fig. 3-5), the model highlights essential differences between predominantly technology-centered digitalization and digitally driven transformation that is managerially integrated and grounded in process analysis. This perspective aligns with the widely supported view in the digital transformation literature that technology creates value only insofar as it is embedded in organizational processes and decision-making (Mencacci et al., 2023; Westerman et al., 2014).

A key result concerns the central role of operational process controllability (C_p) in determining the overall digital transformation success score. Both the linear form analysis (Figure 3) and the multiplicative form analysis (Figure. 4) indicate that variations in (C_p) lead to significant changes in S_{DT} , regardless of the scenario considered. Digital transformation is closely linked to process reconfiguration and governance, rather than merely to technology implementation (Bharadwaj et al., 2013; Westerman et al., 2014). In the multiplicative form, this effect is amplified,

and low levels of (C_p) generate critical bottlenecks that constrain the overall score even in the presence of high values of strategic alignment, indicator use, or technological investments. From a domain-specific perspective, this logic is particularly relevant for medical laboratories, where quality and competence requirements impose strict control and traceability across the entire pre-analytical–analytical–post-analytical chain (International Organization for Standardization ISO, 2022).

The comparison of the two functional forms highlights the difference between a compensatory and a non-compensatory aggregation logic. The weighted linear form allows partial compensation of a low level in one dimension by higher values in others and is, in this respect, suitable for aggregated digital maturity assessments and general comparisons across organizations. This approach is consistent with the practice of maturity index–type evaluations, which enable the assessment of process development and stability by positioning organizations along progressive maturity levels that reflect their capability to manage, measure, and sustainably improve performance, as well as with the digital strategy literature, which often proposes additive composite indicators that are easily interpretable from a managerial perspective (Bharadwaj et al., 2013; Westerman et al., 2014).

By contrast, the multiplicative form explicitly penalizes structural imbalances and is more appropriate in contexts where certain dimensions are non-negotiable from a quality and compliance standpoint. This perspective is consistent with the notion of critical constraints and with the formal quality requirements applicable to medical laboratories (International Organization for Standardization ISO, 2022). Accordingly, the model provides a theoretical justification for selecting the functional form based on the evaluation objective: managerial synthesis (linear) versus explicit penalization of imbalances (multiplicative).

In figure 5 its illustrated the marginal sensitivity analysis of the linear model, witch reinforces the managerial interpretation of the relative importance of the dimensions. Since the partial derivatives of the function are equal to the associated coefficients, the relationship $\beta > \delta$ formalizes the idea that improving process controllability has a greater marginal impact on digital transformation success than increasing technological investments. This conclusion is consistent with the classic argument in the managerial literature that “strategy (and organizational change), not technology per se, drives digital transformation” (Kane et al., 2015), as well as with synthesis studies showing that performance depends on aligning digital initiatives with organizational objectives and integrating them into governance and decision-making processes (Mencacci et al., 2023; Westerman et al., 2014).

For this reason, the model provides a formal framework that goes beyond many descriptive or fragmented empirical approaches by explicitly quantifying the relative impact of organizational versus technological dimensions.

Compared with prior research, the contribution of the model is two main fold. First, it proposes an integrative mathematical formalization of recurrent dimensions in the digital transformation literature (strategic alignment, processes, indicators, and investments), which are frequently discussed separately or operationalized in a heterogeneous manner (Mencacci et al., 2023; Westerman et al., 2014). Second, it explicitly integrates managerial quality practices all into the evaluation framework, making it more suitable for regulated and compliance-oriented contexts such as medical laboratories (International Organization for Standardization ISO, 2022).

Nevertheless, the limitations of the theoretical framework must be explicitly acknowledged. The results discussed are illustrative in nature and do not substitute for empirical validation, and

the weights employed are normative and dependent on domain expertise. These limitations are consistent with the positioning of the paper as a framework paper and open clear directions for future research, such as empirical calibration of coefficients, robustness testing on samples drawn from comparable laboratories, and evaluation of practical usefulness as a benchmarking and decision-support tool (Mencacci et al., 2023; Westerman et al., 2014).

Moreover, the model is compatible with the updated requirements of ISO 15189:2022, which emphasize a process-based approach, risk management, and the role of information systems in quality assurance (International Organization for Standardization ISO, 2022).

Overall, the discussion supports the view that digital transformation success in medical laboratory services is predominantly managerial and process-oriented, with technology acting as a facilitator of process control and indicator-based decision-making, rather than as an exclusive determinant of performance (Verhoef et al., 2021; Kane et al., 2015; Westerman et al., 2014; International Organization for Standardization ISO, 2022).

Conclusion

The article described an integration of theoretical and mathematical models for the study of digital transformation success for medical laboratory services in a high quality, safety, and compliance context. By formalizing the connections between organizational, process-related and technological dimensions without reducing digital transformation to a purely technological perspective, this study fills an important gap in existing literature.

In this model, digital transformation success is defined as managerial and process performance directly resulting from an integrated alignment of digital technologies into operational processes and strategic decision-making. The systematic analysis of these interdependencies relies on integrating the four basic constructs: strategic alignment, process controllability, decision-support use of indicators, and technological investments by a mathematically formalized composite indicator.

Model theoretical analysis in both a weighted linear form and a multiplicative form underpins more structured differences between compensatory logic which is meant for aggregated maturity assessments and non-compensatory logic that explicitly punishes imbalances as well as signalling the existence of critical bottlenecks in process control. The study found that process controllability and the use of decision-support indicators overshadowed technology investments, albeit the marginal sensitivity analysis of the model confirmed this central finding.

The proposed framework does not contain any empirical validation, as it is intended to be applied sequentially on real data in subsequent research to empirically derive the coefficients. In this sense, it helps to build a solid mathematical theoretical foundation towards evaluating digital transformation maturity and future empirical advances in medical laboratory services.

Acknowledgements

This research was supported by the National University of Science and Technology POLITEHNICA Bucharest, Doctoral School of Industrial Engineering and Robotics, through the doctoral grant awarded by the University. The funding institution had no role in the study design, data collection and analysis, decision to publish, or preparation of the manuscript.

During the preparation of this work, the author(s) utilized ChatGPT 4 to enhance readability and language clarity. Following the use of this tool, the author(s) meticulously reviewed and revised the content as necessary and assume(s) full responsibility for the final content of the publication.

Ethical statements

The main author acknowledges professional experience gained as a Senior Brand Manager role within organizations involved in the management of medical laboratory networks operated by Regina Maria and Poliana in Romania. This experience contributed to an informed understanding of the managerial and organizational specificities of medical laboratory services, without involving the use of any proprietary or confidential data.

The use of generative artificial intelligence tools was limited to language editing and clarity improvement. All scientific content, data analysis, and interpretations are the sole responsibility of the authors.

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