Construction Project Management System (CPMS): An Ontological Framework

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***Abstract*—This paper presents on ontological framework to envision a construction project management system (CPMS). The framework has five dimensions: Outcomes, Stages, Resources, Processes and Management techniques. Each dimension is defined by a taxonomy derived from the literature and practice. The dimensions are ordered left to right such that a meaningful natural language sentence describing an attribute of CPMS can be concatenated by selecting a word from each column and combining the selected words with the words interleaved between the columns. There are 11,970 potential CPMS attributes encapsulated in the ontology. Ideally a CPMS should emphasize all of them; practically it will likely focus on a subset selected based on the characteristics of the project and its environment. The challenge in designing a CPMS is to include the key attributes and exclude the less important ones. The ontology will help make these systemic choices systematically by displaying all the possibilities. However, in doing so, one has to consider the interactions among the categories of a dimension and between dimensions. These interactions play an important role in the dynamics of CPMS. The paper discusses some illustrative interactions.**

Keywords-construction project management; ontology; envisioning; systems approach

I. INTRODUCTION

Construction project management is a child of project management which in turn is a child of management. It acquires, adapts, and applies techniques from its parent disciplines to improve the efficiency and performance of construction projects. Early in its history project management was anchored on a few key techniques such as PERT (Project Evaluation and Review Technique) and CPM (Critical Path Method); GANTT charts and PERT charts were the icons of project management. Today, the range of specialized techniques deployed has increased dramatically; it includes stakeholder management, scope management, risk management, waste management, and many more. This growth reflects, on the one hand, the increasing scale, scope, and complexity of construction projects, and on the other, the increasing requirements, regulations, and the rate of change of the construction environment. Effectively integrating the portfolio of specialized techniques for managing a construction project requires a systemic approach – a construction project management system (CPMS). Such a system is needed to exploit the interdependencies and synergies between the techniques, prevent shortsighted strategies, avoid dysfunctional unintended consequences, and forestall unrecoverable systemic failures. It has to reckon with the actuality of the complex projects [1].

The challenge of developing a CPMS can be illustrated using the parable of the six blind men and the elephant. Six blind men, wanting to know an elephant, touch different parts of the elephant and declare the elephant to be like a rock (body), pillar (leg), rope (tail), arrow (tusk), fan (ear), and tree (trunk). While the men are debating their different perceptions a wise man intervenes. He affirms all six perceptions and explains how each is about a part of a whole elephant which they do not see. Just like the wise man that sees the whole elephant and settles the debate among the blind men, there is a need for a wise vision of the project management system. Without a singular vision of CPMS but the fragmented application of techniques can be dysfunctional. How the CPMS is envisioned will determine how the project is managed as a whole. The challenge is to envision the system from its parts, and fit the parts to the whole. We propose an ontological framework to help the project manager make the CPMS 'elephant' whole and visible.

II. ONTOLOGY OF A CPMS

Ontologies are used to systematize the description of complex systems[2] ; they are an "explicit specification of a conceptualization." [3]The following is a brief description of ontological analysis and design:

"We will define [an ontology] as a logically constructed n-dimensional natural language description of the problem. The dimensions are derived from the problem statement. Each dimension is independent of the other and is a taxonomy of discrete categories. Each taxonomy may be flat or hierarchical. Further, the order of categories in a particular dimension at a particular level of the taxonomy may be nominal (no particular order) or ordinal (based on some parameter). The stages of progression along the dimension, the sequence of evolution, the progressive part-whole relationships, the scale, etc. are some bases for ordering the categories. Last, a dimension may have sub-dimensions with their own taxonomies. That is, a dimension itself may be hierarchical."

The ontology is presented as a number of text columns, each column representing a dimension of the problem …. It is in fact an n-dimensional matrix with text entries in each cell. Each column contains categories and subcategories corresponding to the taxonomy of that dimension. A combination of categories or sub categories across all the dimensions, with specified prepositions and conjunctions, is a natural language descriptor of a component of the problem in the form of a sentence, sometimes an awkward sentence. The set of all combinations across all categories – that is all possible sentences – is a closed description of the problem. The full set can have a very large number of descriptors (individual combinations). However, many of the combinations may be irrelevant or meaningless – they may be discarded from further consideration. At the same time some combinations may be novel and creative, providing valuable insights into the problem and its solution.

A parsimonious choice of dimensions, taxonomies of dimensions, and selection of combinations (with appropriate prepositions and conjunctions) is essential for effective formulation and solution. The formulation can be modified or extended by substituting or adding new dimensions, new taxonomies, and new categories and subcategories within taxonomies." [4]

The proposed ontology of CPMS is shown in Figure 1. It has been developed by analyzing and organizing the key dimensions of project management systems embodied in PMBoK [5] and the published literature. We will describe the ontology in the following.

The five dimensions of the ontology are represented by the five columns in the figure. They are:

- Outcomes: These are the outcomes generally desired in projects. They are broadly classified as efficiency and performance outcomes. Efficiency outcomes, in turn, are usually measured with reference to cost and time. While the efficiency of use of other resources could be included in the list (the ontology is easily extensible), most of them usually devolve to cost in the final measurement. Similarly, performance outcomes are measured in terms of quality, safety [6], sustainability [7, 8], and satisfaction [9]. The taxonomy reflects the evolution of desired construction project management outcomes – sustainability and satisfaction outcomes are of recent origin. As with efficiency, other categories of performance can be added.
- Stages: The three broad stages of a project are conceptualization (or visualization), construction, and closing. Each of these stages can be further refined with subcategories, or the dimension can be extended with additional categories. Construction, the object of this research, has been subcategorized into de novo or new construction, demolition, deconstruction, and reconstruction. This choice of subcategories of construction in a project will affect the design of its CPMS. The three stages are sequential with feedback processes linking a subsequent stage to the previous stages, and feedforward processes linking the prior stages to subsequent stages. Thus, as construction proceeds there could be some reconceptualization based on feedback and the need to adapt to unexpected environmental conditions; and as segments of the project approach closing there could be reconstruction to correct errors or reconceptualization to fit changed expectations. The feedback will help achieve the desired outcomes. Similarly, conceptualization can inform construction, and construction can inform closing through feedforward mechanisms to obtain the desired outcomes.
- Resources: The seven types of resources a construction project has to manage are time, manpower, material, space, cost, information, and energy. The subcategory of equipment is listed under material to highlight its importance in construction. It must be noted that information is a key resource in any CPMS – the success of the system will depend upon how well it can informate (convert into information) the other resources. Thus, for example, the outcome of CPMS will depend upon the reliability and validity of the information it has about manpower, not on the actual manpower. The taxonomy of resources can be extended with more categories or deepened with refined subcategories.
- Processes: The three classic processes underlying any project management are planning, monitoring, and control – they form the essence of PMBoK [5]. They are listed in that order. The processes are sequential, continuous, and iterative. They form a negative feedback (in the cybernetic sense – not negative reinforcement) mechanism seeking to eliminate deviations from the desired outcomes. Planning specifies the outcomes, monitoring determines the gap between the desired and actual/anticipated outcomes, and controlling acts to eliminate the gap. The processes are almost entirely information-based further emphasizing the role of information resources in a CPMS.
- Management techniques: The dimension lists a range of management techniques likely to be used in a construction project (see for example [10-15]. They are listed in the order in which they are likely to be introduced into the project. They also reflect the specialized knowledge needed to manage a modern construction project, a feature further highlighted by the introduction of Knowledge Management itself as a management technique. The techniques are not mutually independent of each other – there is likely to be a strong interaction between them. For example, procurement management and logistics management are likely to be strongly dependent on each other. A CPMS has to minimize the dysfunctional interactions and maximize the functional ones.

Process		Resources		Stages		Outcomes		Management Techniques
Planning	[+]	Time	[during]	Conceptualization	[for]	Efficiency	[using]	Stakeholder managemement
Monitoring		Manpower		Construction		Cost		Scope Management
Controlling		Material		De novo		Time		Communication Management
		Equipment		Demolition		Performance		Cost Management
		Space		Deconstruction		Quality		Schedule & Time Management
		Cost		Reconstruction		Safety		Procurement Management
		Information		Closing		Sustainability		Tender Management
		Energy				Satisfaction		Human Resource Management
								Logistics Management
								Risk Management
								Change Management
								Contract Management
								Quality Management
								Claims Management
								Vendor Management
								Needs Management
								Integration Management
								Waste Management
								Knowledge Management

Illustrative components of a Construction Project Management System

Planning time during conceptualization for efficiency using scope management.

Monitoring manpower during construction for performance $_{\text{safety}}$ using contract management.

Controlling cost during closing for performance $_{\text{sustainability}}$ using waste management.

Planning cost during constuction$_{\text{deconstruction}}$ for sustainability using waste management.

Figure 1: Ontology of a Construction Project Management System (CPMS)

III. Envisioning a CPMS

The dimensions are ordered left to right such that a meaningful natural language sentence describing an attribute of CPMS can be concatenated by selecting a word from each column and combining the selected words with the words interleaved between the columns. Three illustrative sentences are given at the bottom of Figure 1, with subscripted words used to indicate subcategories in the ontology. They are:

- Planning time during conceptualization for efficiency using scope management: A CPMS which plans for time as a resource at the conceptualization stage itself while managing the scope of the project will likely increase the time efficiency of the project.
- Monitoring manpower during construction for performance $_{\text{safety}}$ using contract management: A CPMS which has built in provisions in the contract for monitoring the manpower for safety (for example, training for safety and use of safety equipment) is likely to increase the performance safety of the project
- Controlling cost during closing for performance $_{\text{sustainability}}$ using waste management: A CPMS which controls closing costs using waste management techniques to ensure sustainability is likely to be effective in performance$_{\text{sustainability}}$.
- Planning cost during construction$_{\text{deconstruction}}$ for sustainability using waste management: A CPMS which helps plan for deconstruction costs to assure performance $_{\text{sustainability}}$ using waste management techniques.

There are 11,970 potential CPMS attributes encapsulated in the ontology. Ideally a CPMS should emphasize all of them; practically it will likely focus on a subset selected based on the characteristics of the project and its environment. The challenge in designing a CPMS is to include the key attributes and exclude the less important ones. The ontology will help make these systemic choices systematically by displaying all the possibilities. However, in doing so, one has to consider the interactions among the categories of a dimension and between dimensions. These interactions play an important role in the dynamics of CPMS. In the following we will discuss some illustrative interactions.

Though one may seek to maximize both efficiency and performance, there is usually a tradeoff between the two. For example, there is a threshold beyond which quality, safety, sustainability, and satisfaction are likely to become cost and time prohibitive [16, 17]. It is necessary to know the relationship between these measures to be able to make an informed choice. These choices may have to be revisited at each stage, namely: conceptualization, construction, and closing. New information which becomes available as the project progresses has to be factored into the tradeoff. Thus, an architect may be compelled to compromise on the high expectations for quality he/she had set during conceptualization due to lack of the requisite skilled labor during construction – acquiring the labor could be cost prohibitive.

A variety of management techniques may be deployed to establish the profile of desired outcomes. Stakeholder management could help determine the priorities of the architects, the designers, the builders, the customers, the regulators, etc. Quality management can be used to set quality requirements while needs management can be used to set user/customer expectations. The diverse techniques will likely provide a wide range of outcome criteria, some of which may be in conflict with one another; it is necessary for the CPMS to reconcile them to ensure a convergence of outcome measures.

It is the task of the project manager to map the outcome measures to the resources as part of the process of planning, monitoring, and controlling the project. The precision and accuracy of the mapping will depend upon the project, the environment, and the knowledge of the CPMS. For this reason knowledge management (listed as a technique) [18] can play a key role in the CPMS. At the same time the absence of or incorrect information/knowledge can be the source of uncertainty and risk, necessitating systematic risk management.

Thus, the ontology provides a framework to systematically explicate the interactions between and within dimensions. In addition to documenting the known interactions it compels the project manager to consider that may have been overlooked: for example, 'planning information during conceptualization for performance safety.' If safety is a high priority outcome it would behoove the people conceptualizing the project to proactively plan for information to ensure the same. Otherwise, the information may not be adequate or appropriate to monitor and control safety.

In summary the ontology is a concise, comprehensive, and comprehensive framework for envisioning a CPMS. In the following section we will illustrate how the ontology can be used to develop a CPMS.

IV. Application of the CPMS Framework

The CPMS framework can be used to systematically analyze the interactions between its dimensions and address them systemically. We will illustrate such analysis with a discussion of Outcome vs. Resource interactions, Process vs. Resource interactions, and interactions between techniques. We will demonstrate how these interactions can be mapped to permit easy visual analysis, interpretation, and decision making.

A. Outcome-Resource Interactions

The priority of outcomes and the requirement of a project will determine the priority of resources. The interaction of outcomes and resources can be mapped as shown in Figure 1 below to highlight the critical ones to be monitored in the project.

The Outcome categories and subcategories in the ontology are listed in the second and third column from the left; the rank order of the subcategories' priority is shown in the rightmost column. Thus, in the figure cost efficiency is ranked above time efficiency; satisfaction is ranked most important for performance and safety is least important. The ranking may change with project type – a residential house may give higher priority to cost than time; a residential housing complex may give equal priority to cost and time factoring the time value of money invested in the project.

The Resources specified in the ontology are listed in the third row from the top. The top row ranks the priority of resources. In Fig. 2 Cost is ranked most important and Space the least important resource. These priorities too will vary by project – Equipment may be the most important in a specialized construction project or space may be the most important for the construction of a high rise building de novo in a densely populated business district.

The interaction between outcomes and resources is color coded in the figure – red is most important, orange is less important, yellow is least important, and grey is neutral. Thus in the figure manpower and material resources affect cost

			5	2	3	4	8	1	6	7	←priority of resources
			Resource								
			Time	Manpower	Material	Equipment	Space	Cost	Information	Energy	↙ priority of outcomes
Outcome	Efficiency	Cost									1
		Time									2
	Performance	Quality									2
		Safety									4
		Sustainability									3
		Satisfaction									1

Figure 2: Outcome-Resource Interactions

efficiency the most; time, equipment, and energy the least; space, cost (financial resources), and information resources have an intermediate effect. Similarly, satisfaction – the highest ranked performance outcome – is most dependent upon time, material, equipment, and cost (financial resources); it is least dependent upon manpower, space, and energy. The figure highlights the importance of managing (cells in red), for example: (a) manpower and material costs, (b) material delivery – time efficiency, (c) manpower, material, and equipment quality and cost of quality, (d) sustainability of equipment, and (e) satisfaction with timeliness, material, equipment, and cost.

The priorities and intensity of interactions in the Outcome x Resources matrix will depend upon a number of factors. Some of them are listed and briefly discussed below.

- Type of building: The priority of outcomes is likely to be different for an individual residence, a residential complex, a commercial complex, a hotel, a hospital, and an infrastructure project. An individual building his or her 'dream home' may be more willing to trade cost and time efficiency for quality and satisfaction performance. Thus, managing cost as a resource may be less important than managing manpower and material resources which affect quality and satisfaction. On the other hand, a capital intensive commercial complex may be far less willing to sacrifice cost and time efficiency due to the high cost of capital incurred. Thus, managing the financial costs may be as important as managing manpower and material.

- Project sponsor: A sponsor who is an end user is likely to have different priorities as against a sponsor who is just an investor. An individual residence is likely to be financed, built and used by the same person; on the other hand, a residential complex is likely to be financed, built, and used by different stakeholders. These differences will lead to different priorities of outcomes as well as resources, and interactions between the two.

- Stakeholders: Projects with few stakeholders are likely to have clearer priorities than projects with many stakeholders. When stakeholders change due to environmental changes or advancement of the project phase the priorities and interactions may change.

- Project stage: The priorities and interactions may change at different stages of the project. Energy sustainability may not be important in the construction phase but important in the operation phase.

- Location of the project: The resource restriction/abundance based on the location of the project could affect the priorities and interaction. Space may be a critical resource for an urban project but not for a green field project.

- Market dynamics: Changes in market conditions could change the business case for the project and hence the priorities and interactions. For example, safety performance may become critical due to new laws or increased scrutiny instigated by a spate of construction accidents.

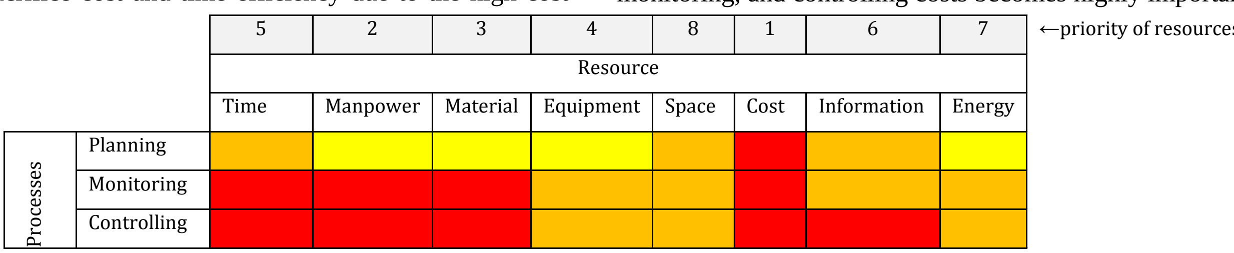

Figure 3: Process-Resource Interactions

B. Process-Resource Interactions

The importance of the three processes: planning, monitoring, and control can vary by resource priority as well as its characteristics. Resources with higher priority naturally require more attention than those with lower priority. Further, abundant resources or those with well established supply chains may require less planning but more monitoring and control, whereas resources in short supply may require considerable planning. The interaction of processes and resources can be mapped as shown in Fig. 3.

When cost efficiency is a high priority outcome, planning, monitoring, and controlling costs becomes highly important. At the same time, if energy is abundant and its cost is a small fraction of the total cost planning for energy may not be very important; monitoring and controlling it may be somewhat important. Similarly, in a controversial project planning and monitoring information may be somewhat important and controlling the information disseminated to the stakeholders may be very important.

As in the case of Outcome-Resource interactions the Process-Resource interactions can be determined by many factors intrinsic to the project as well as external to it. An urgent project (for example the completion of the Commonwealth Games facilities in the last stages) may place very high emphasis on planning, monitoring, and controlling time to the exclusion of other resources. A marquee project (for example, the Delhi Metro) may place almost equal emphasis on planning, monitoring, and controlling all the resources rendering the whole matrix red.

In planning process, space utilization needs to be optimized for given input cost. Many project's stakeholders are more often inconvenienced during planning and monitoring process due to excess utilization of space. The ground usage for logistics requirements during the construction of a 'metro rail line' or a 'high-rise' project during its initial stages is maximum, but for limited duration of the project, hence, best kept at minimum.

C. *Interaction between techniques*

The construction project management techniques do not act independently, they interact with each other. The interactions among them can be mapped and visualized using the matrix in Fig. 4. The most important interactions are shown in red, less important in orange, least important on yellow, and neutral in gray.

- When there is a change in the interior designs of a hotel project while the project is under execution, one would immediately look at its impact on the schedule, cost, new procurements etc. Focus is on communication, waste, knowledge management. When the project is in the initialization stage, the impact of this decision is focused on cost, communication and procurement, while the impact on project needs constructability, logistics, and quality is out of focus.
- When a procurement item during the initial process is delayed due to strategic reasons time Vs cost interaction, then stakeholder, communication, needs, risk at project sites etc are out of focus.

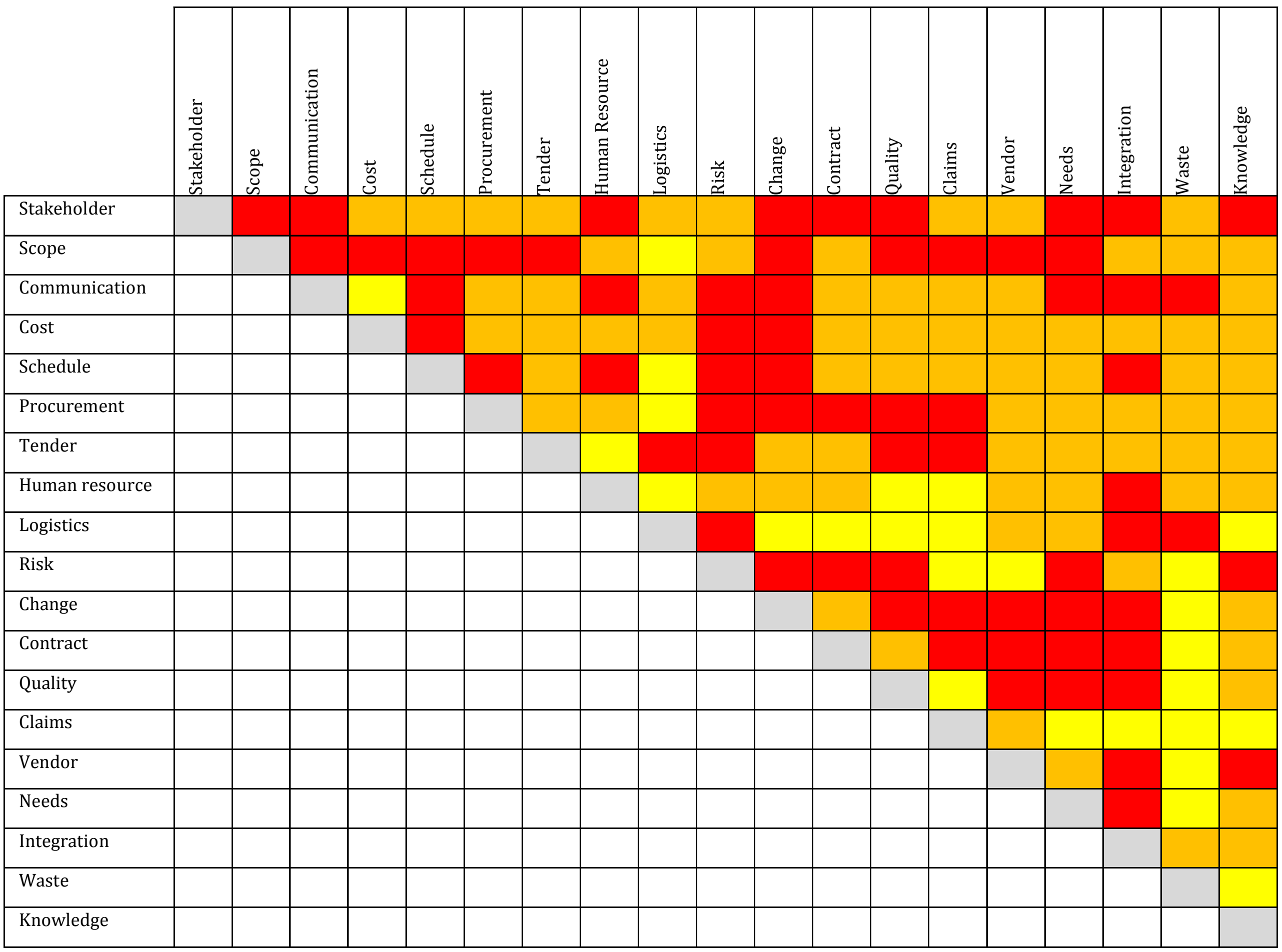

Figure 4: Interaction between Techniques

For an effective construction project management system it is necessary to know and understand the interactions and the consequent cascading outcomes. Often, the managers use the techniques individually and seek the desired outputs; seldom do they look at interactions which are not in immediate focus and which may lead to functional or dysfunctional unintended effects. By focusing on the individual techniques and their interactions this matrix can act as a checklist for assurance for achieving project's intended goals. Following are some illustrations:

- When decision on change in vendor for a particular work is decided due to non-performance time, risks, cost and time are in focus. Integration needs, communication, contract management is out of focus.
- When construction debris is disposed, logistics, need, claims and scope is looked at. Integration, knowledge, waste, cost, and energy management is at the backburner.

- When material procurement is done in bulk for price advantage, cost, time, procurement, is traded. Logistics, waste, quality, scope is not looked at.
- While tracking the needs of the stakeholder, documented in the scope documents, implicit requirements are not clearly define in the project. While the implicit needs are identified in project execution phase its interactions with all other management are not visited. The triad of scope-cost-time is always in focus.
- Vendor in projects are result of project procurement process. While execution, cost, time, scope, claims etc are in focus. HR practices, knowledge and logistics are not focused resulting in varied performances. (Vendor's teams on projects are often not considered as a stakeholder as they are from different organization, out there to deliver their scope. Motivation, learning, knowledge sharing, waste management, logistics and risk management needs to be concentrated.

V. Conclusion

The next step in the evolution of construction project management is to conceptualize the management techniques as part of a larger system which we have called the Construction Project Management System. Envisioning such a system and implementing a systemic as well as systematic approach to construction project management will be important to effective management of increasingly complex projects in a turbulent environment. The proposed ontological framework will help deconstruct the complexities, understand the interactions, and manage them effectively. The framework itself is modular and extensible. It can be modified and adapted as necessary to different projects. A major advantage of the framework is its concise yet complete representation of the underlying complexity of CPMS. It enhances the face validity of the framework and makes it easy to apply. It minimizes the potential errors of omission and commission in the design of a CPMS.

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