

Article

A Framework for Defining and Developing Capabilities for Operations and Maintenance of Infrastructure Assets

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Abstract

Infrastructure asset management faces major challenges in maintaining ageing assets while adapting to technological changes and budget constraints. This paper addresses the lack of a clear definition for “operations and maintenance (O&M) capability” in the context of infrastructure asset management. The authors conducted a systematic literature review extracting 13 capability definitions across multiple domains, followed by semi-structured interviews with 11 senior industry experts from diverse infrastructure sectors, analysing data through List–Group–Label methodology. The research resulted in a comprehensive yet practical definition of O&M capability and identified its key components through an expert-refined framework that balances comprehensiveness and simplicity. This definition provides practitioners and researchers with a common understanding that enables better adaptation of infrastructure to rapid technological change, better utilisation of data and a stronger focus on citizen needs. The framework enables cities and infrastructure operators to systematically assess, develop, and communicate their O&M capabilities, supporting standardised approaches to capability planning and performance measurement across smart city infrastructure projects. The framework creates a foundation for future research and practical applications in O&M and stimulates further development of approaches to build capabilities for smart city infrastructure.



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Keywords: infrastructure assets; information and communication technology; transportation technologies; urban mobility; operations & maintenance; organisational capabilities; capability definition; organisational planning

1. Introduction

Operations and maintenance (O&M) capability building, such as stakeholder connectivity capability, integrated information capability and technology absorption capability, is high on the agenda for organisations that operate and maintain transportation assets in smart cities, as it directly impacts asset performance, operational efficiency, and long-term value [1,2]. Organisations that own mature assets are starting to realise that they cannot simply sidestep the challenges posed by ageing assets, changing environmental and social conditions, and budget shortfalls. As a result, they are turning their attention to better managing the assets they already own.

However, a review of the literature on building capabilities within organisations that operate and maintain infrastructure assets found that a precise definition of the concept of O&M capability is lacking. It is unclear what the term “capability” stands for and

what the concept means in the context of organisations responsible for operating and maintaining infrastructure assets. Although the term is used daily, its meaning is often confused with similar concepts. While the concept of capability in organisations has been studied extensively and several definitions exist, these are either tailored to other industries or are generic.

To identify and build O&M capabilities, we need to be able to communicate about them. To do this effectively, we need to start from the same understanding of the core concept of “operations and maintenance capability”. By creating a definition of the concept, we will provide the practitioners with a common understanding. By perceiving or conceiving and then abstracting objects, we obtain concepts, which are represented by designations and/or definitions. Designation, definition, and the concept all refer to the same object(s) making up the extension (the set of objects a concept extends to or applies to). Definitions make it possible to pick out the extension and distinguish the concept from others within the domain. Designations are a concise way of referencing a concept [3]. Therefore, to communicate effectively about O&M capabilities, we need to define, represent, or describe the concept of O&M capability through both a definition and a designation.

When searching for the term capability, we can find a large amount of literature on the subject. However, the literature encompasses materials which talk about the concept of capability from many different perspectives. Henshaw et al. [4] treated the term capability as a polyseme, meaning it has multiple distinct, but related meanings. To express these meanings better, different authors have put forth different names and definitions for the concept. Papazoglou [5] explores different definitions of the concept and presents them in an ontology domain model, through which he clarifies the relationship between various terms within the domain. Henshaw et al. [4] discuss and define eight worldviews (points-of-view) on the concept of capability, from the systems engineering perspective. They go on to define an entity-relationship diagram for the concept of capability engineering, which clarifies the relationship of the term capability with other terms within the domain.

Researchers use different approaches to define the concept of capability for their context. Henshaw et al. [4] present the multitude of meanings of the concept, based on the context, which are explored through a soft systems methodology. For each perspective a definition is created and agreed. Cosic et al. [6] begin with an established definition and extrapolate it to fit their needs. Zawislak et al. [7] define their capability as a combination or result of other, already defined capabilities. Another approach is to analyse a list of existing capabilities to synthesise the key elements and then integrate them with the subject matter field, to create a new definition for a specific context [8,9].

The primary objective of this paper is to define O&M capability and explain its key concepts. To achieve this, we first identify core elements relevant to defining capabilities in general, using the List–Group–Label methodology. We then propose a generalised formula applicable across various domains. Next, we adapt these key concepts specifically to the context of O&M within transportation infrastructure. Finally, based on this analysis, we present a novel definition of O&M capability that provides practitioners with a common understanding and facilitates targeted development efforts.

2. Background

2.1. Challenges to Modern Transportation Networks in Smart Cities

Infrastructure networks are a complex system of systems [10]. They bring together different assets, which together enable a modern way of living. This is especially true in cities, where so many different services inter-relate and need to integrate. From transport of people and goods to availability of clean water, electricity, etc. Working infrastructure has a positive economic impact across every sector [11,12]. Thus, it is paramount that we

keep them in the best shape possible. Failing to do so could have far reaching, progressive and cascading impacts. From safety issues to business productivity, GDP, employment, personal income, and international competitiveness.

Smart Cities' initiatives look to make cities more liveable for all. The goal is to build a seamless, equitable experience for the citizens, by optimising the services they use and even predicting their needs. This results in improving resource utilisation, thus making the cities greener, more energy efficient and reducing their environmental impact. By integrating existing infrastructure assets with advanced technologies, new levels of agility, efficiency, sustainability, and resilience can be achieved. Decisions about how to utilise (operate) and maintain infrastructure assets can be made much faster, even in real-time. This is enabled by connecting various types of real-time data collection techniques into the Internet of Things and utilising advanced data analysis techniques to gain better insights from the integrated data. Multimodal, real-time, energy efficient public transport system, able to respond to urban challenges, such as climate change and rapid urbanisation, thus becomes achievable through robust O&M capabilities.

Infrastructure assets are characterised by long lives and big upfront investments needed to procure them [13,14]. Major parts of infrastructure networks of developed economies have been built in the second half of 20th century and are reaching the ends of their useful lives [15,16]. Today, our networks are so expansive, we only add about 0.5% to value of our asset stock annually [17]. Due to the size of networks, the impact of the acquisition of new capital assets has fallen, and the return on investment has diminished. At the same time, due to the ageing of existing assets, their performance is falling, and they require more intervention to provide the required level of service [18–20]. Despite the huge initial investments needed to procure capital infrastructure assets, their whole life costs are much bigger [21]. Thus, the gap between required and available funding is getting bigger and will only increase without intervention [22–24].

Transportation networks in cities have been optimised to cater for specific demand patterns, characterised by location, time, volumes, etc. These patterns are being challenged by a number of impacts. Climate change will affect how we design, build and manage our infrastructure [25]. The shift from commuting to and from the office every day has been happening for some time now [26]. COVID-19 outbreak, and the resulting lockdowns have impacted those patterns heavily [27]. People are less likely to commute, they use more heating, electricity, and internet at home throughout the day as opposed to just evenings or weekends. On the business side, organisations are turning to local supply chains, which may impact volumes of materials going through ports, etc. [28,29]. Smart cities look to change such static optimisations to dynamic demand patterns, thus re-aligning the offered services based on real-time data, which reflects the citizens' needs. This is resulting in integrated, multimodal and intelligent systems, focusing on mobility, reduced congestion and sustainable urban growth [30,31].

Based on this, resilience is becoming an important factor in everything we do [32]. Ganin et al. [33] imply that to select road projects, efficiency should not be the only considered factor, but also resilience. They found that many under normal conditions inefficient road networks are more resilient to disruptions than some more efficient ones. In the US, at least 25 major cities and states have chief resilience officers, and their infrastructure is graded, amongst others, on resilience [11]. During the COVID-19 outbreak, shortcomings in the ability to manage and operate transportation assets in cities have been revealed [34,35]. Kim et al. [36] found that environments with a better ICT infrastructure show greater resilience [37]. Resilience is also important in the context of natural disasters [38].

It is unclear how different infrastructure assets will be affected by coming changes, however considering the declining budgets, ageing infrastructure assets, stricter legisla-

tion, and the technological advancements, cities managing these will need to find ways to adapt themselves to the changing requirements faster, more frequently, and more efficiently—therefore, they must become smarter.

2.2. *Shifting Priorities: From New Construction to O&M*

Looking at the road network in the US, despite extra investment over the 2009–2017 period, its condition has declined. This is in part due to the funding being spent on new roads, rather than improvement of the condition of existing roads. However, the trend is changing as the investment in repair and preservation has increased between the period of 2004–2008 and the period of 2009–2014. The Repair priorities report recommends four actions on the national level, all of which prioritise the investment in maintenance [20]. Investment in better O&M may be the better and more cost-effective approach, as it improves utilisation, efficiency, and longevity of existing infrastructure assets [39]. As opposed to capital asset procurement, O&M solutions are often more affordable and cost-effective. Even small improvements, such as the investment in ICT for O&M, can have significant impact due to the size of asset networks in cities [40].

However, to save costs, maintenance often gets deferred, which results in maintenance backlogs, which continue getting bigger, if not addressed [41,42]. This puts users' safety, and organisations' and nations' economic bottom-line at risk [43]. Examining the US road network, it continues to be an issue [11]. Maintenance backlogs in combination with changing climate and usage conditions result in even faster asset deterioration and shorter useful life [44].

The World Economic Forum has identified “build capabilities” as one of the key enablers of their O&M best practice framework [39]. Building capabilities is essential to organisations being able to act on their vision and strategy [45].

2.3. *Building Capabilities Through Planning*

Military organisations are some of the most complex and advanced organisations in the World. To build capabilities within military organisations, a Capability-Based Planning (CBP) methodology has been developed [46]. From their perspective, CBP is planning under uncertainty, to provide capabilities suitable for a wide range of modern-day challenges and circumstances while working within an economic framework that necessitates choice [47]. This definition goes hand in hand with the context of modern challenges cities face. External influences, such as climate change, impact of COVID, etc., provide for a wide plethora of new challenges, whilst the budgets transportation asset owners have available are restrictive.

CBP focuses on policy objectives rather than point scenarios, to help identify and develop capabilities needed to achieve strategic objectives in a volatile environment. It is a risk management framework that provides a rational basis for development of an organisation in a context of uncertainty and budgetary constraints [48,49].

It attempts to break down traditional stovepipes and provide for transparency and coherence and encourages innovation [50]. It recognises the interdependence of people, processes, and technologies in delivering capabilities, and the need to be able to examine options and trade-offs in terms of performance, cost, and risk to invest optimally [51].

It was developed as an alternative to threat-based planning (TBP), which focuses on single or a small set of specific and identifiable threats (challenges) and develops specific capabilities for those. The main critique of TBP is it may develop specific types of niche capabilities that would be ill suited against other potential operational environments [49].

The Open Group Architecture Framework (TOGAF) standard defines CBP as a business planning technique that focuses on business outcomes. TOGAF standard is an enter-

prise architecture methodology and framework used by organisations to improve business efficiency. It helps align IT goals with business goals. It stresses CBP's relevance from the information technology (IT) perspective, as IT impacts the whole organisation. IT projects are often less successful due to their impact on everything else (business process re-engineering, training, etc.) not being properly managed, and due to their disconnect from business outcomes [52].

The organisations utilising CBP have established a number of definitions of capabilities, each tailored to their specific needs and context.

3. Materials & Methods

For our research, we have chosen a three-stage research approach, consisting of the Identification of key concepts, tailoring of identified key concepts to the O&M industry, and creating a definition of the concept of O&M capability (see Figure 1).

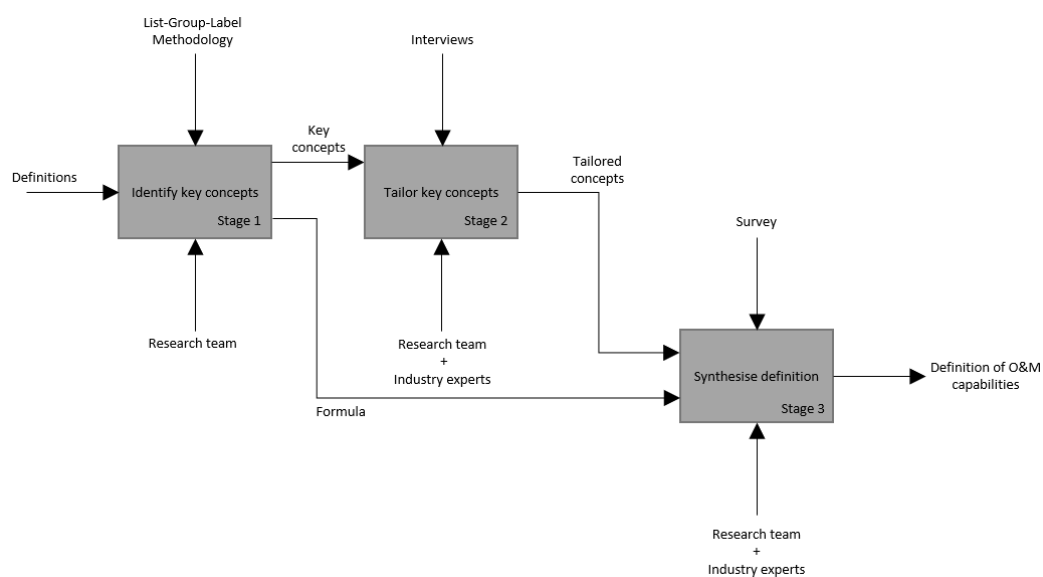


Figure 1. Process of our research methodology.

3.1. Identification of Key Concepts (Stage 1)

The goal of the first stage of the research was to identify key concepts which are used when defining the concept of capability and to synthesise a common structure (formula) for building definitions. To do that, we decided to identify at least 10 existing definitions of the concept of capability. We decided on the minimum of 10 definitions, as other research [8,9], which uses similar methodologies to ours, utilised 10 and 13 definitions, respectively. As a part of the literature review, we conducted an analysis of available sources on Scopus. The goal was to identify the most relevant and high-quality studies for inclusion in our research. To achieve our goal, we decided our approach should progressively filter the results through several rounds of query-based searches. In each round we combined a larger number of keywords, expecting a smaller and more focused set of results. We formulated our literature search criteria based on the relatedness to the O&M disciplines, similarity of the topic, and fundamentality of work. The previous step should identify a small enough dataset to enable the next step, which was a more thorough, manual screening of results based on their titles and abstracts, as well as a more detailed review of the full text of the more promising results.

To identify key concepts, we analysed chosen definitions using the List–Group–Label methodology with the following operationalization:

- **List Phase:** Individual words and word groups representing distinct concepts were extracted from each definition as the unit of analysis. The lead author conducted all coding using Excel spreadsheets to systematically document extracted concepts alongside their source definitions. Concepts were identified based on their semantic meaning within the definitional context.
- **Group Phase:** Extracted concepts were grouped based on logical connections and semantic similarity (i.e., concepts with similar or identical meanings were clustered together). Categories emerged inductively from the data rather than using predetermined frameworks. Grouping decisions were documented in a cleaned Excel table organising concepts into four primary groupings, with frequency analysis conducted to track concept appearance across definitions.
- **Label Phase:** Group labels were selected using either superordinate concepts or same-level concepts that best represented the clustered items. Label selection was documented through systematic analysis of constituent concepts within each grouping.
- **Quality Assurance:** To ensure consistency and validity, the resulting categorization was subsequently validated through consultation with industry experts during the interview phase of the study. This expert validation served as a reasoned alternative to traditional inter-rater reliability measures, given the single-coder approach.
- **Documentation:** Complete audit trails were maintained including: (1) original definitions table, (2) comprehensive concept extraction table, (3) cleaned groupings table, (4) frequency analysis, and (5) labelling rationale documentation.

3.2. Adaptation of Identified Concepts (Stage 2)

The goal of the second stage of the research was to tailor the identified key concepts to the disciplines of O&M. This was done through semi-structured interviews [53] with industry experts. As the targeted interviewees were senior personnel in major industry organisations, we aimed at 10 positive replies. The sample of 10 experts was deemed sufficient as it exceeded the range where basic themes typically emerge (6–12 interviews) according to qualitative research literature [54], while the high information power of these senior experts with specialised knowledge reduced the need for larger sample sizes [55]. To gather the best insights possible, we based our search for the right professionals on the following criteria:

- **Industry:** Organisations which operate and maintain assets within any of the infrastructure industries, as they are all represented and interrelated in cities, and organisations which provides services or products to the infrastructure industries, i.e., supply chain, consultants, etc.
- **Level of seniority within their organisations:** Senior leaders.
- **Years of experience in the infrastructure industry:** More than 15 years (total can be more).
- **Size of organisation:** More than 1000 employees.
- **Location:** Globally dispersed group of interviewees.

Through the interviews we validated the relevance of the key concepts for the O&M disciplines and discussed them in the context of O&M. We conducted the interviews using a semi-structured interview approach. The interviews consisted of a series of prepared questions (see Appendix A) followed by free-form questions and discussions determined by the interviewees' responses. As each of the interviewees spoke about the concepts from their own perspective, we attempted to identify common, underlying themes. By synthesising common themes, we aimed to develop broader concepts that would facilitate the definition of the concept of O&M capability.

3.3. Synthesis of the Findings (Stage 3)

The goal of the third stage of the research was to integrate the key concepts tailored to the infrastructure O&M disciplines in the second stage, utilising the formula from Stage 1, into a coherent definition of the concept of O&M capability. We validated the definition firstly by checking-off each of the requirements for a good definition, as defined by (Wacker, 2004) [56], and secondly by surveying industry experts via a single question, with a YES/NO answer, and a possibility of comment. YES/NO answer was mandatory, whilst the comment was not.

4. Results and Analysis

4.1. Key Concepts (Stage 1)

To comprehensively explore the existing literature on operations and maintenance capabilities, we conducted a systematic search using electronic database Scopus (see Table 1). Initial searches in autumn 2022 aimed to identify the breadth of research on the core concepts. The search term “capabilities” yielded 1,868,233 results, while “operations maintenance” returned 242,621 results. These numbers reflect the broader usage and general applicability of “capabilities” compared to the more specialised focus of “operations maintenance.” The large number of records retrieved in both searches indicated a substantial body of existing literature requiring further refinement.

Table 1. Results from Scopus.

Round	Query	Results
Round 1 (R1)	capabilities (Q1)	1,868,233
Round 1 (R1)	operations maintenance (Q2)	242,621
Round 2 (R2)	capabilities + definition (Q3)	106,002
Round 2 (R2)	capabilities + operations maintenance (Q4)	21,736
Round 3 (R3)	capabilities + operations maintenance + definition (Q5)	2952

To refine our search and identify studies directly relevant to defining operations and maintenance capabilities, we conducted multiple rounds. In round 2, we combined the initial keywords with the term “definition” to specifically target works addressing definitions within the field. The query “capabilities + definition” returned 106,002 results, while “capabilities + operations maintenance” yielded 21,736 results. The high number of results for “capabilities + definition” indicated a significant volume of literature discussing definitions; however, subsequent review revealed that many of these definitions were related to concepts outside the scope of our research focus on capabilities.

Round 3 involved combining all previously used keywords into a single search query: “capabilities + definition + operations maintenance”. This resulted in 2952 records, which, while still substantial, allowed for manageable manual screening.

We combined the identified definitions from the manual screening of the results of our third round of searches on Scopus with other definitions from key professional sources and extracted a total of 13 definitions of “capability” (see Table 2). These include definitions from the military (see numbers 1, 3, and 4), IT (6 and 12), systems engineering (2), asset management (13), manufacturing industry (11), and general (5, 7, 8, 9, and 10) domains.

Table 2. Derived definitions of capability.

#	Definition	Source
1	Capabilities in the MODAF sense are specifically not about equipment but are a high-level specification of the enterprise’s ability. A capability is a classification of some ability—and can be specified regardless of whether the enterprise is currently able to achieve it. For example, one could define a capability “Manned Interplanetary Travel” which no-one can currently achieve, but which may be planned or aspired to. Capabilities in MODAF are not time-dependent—once defined they are persistent. It is only the Capability Requirement that changes.	[57]
2	An outcome or effect which can be achieved through use of features of a system of interest and which contributes to a desired benefit or goal.	[58]
3	The ability to achieve a desired effect under specified [performance] standards and conditions through combinations of ways and means [activities and resources] to perform a set of activities.	[59]
4	A capability is the ability to achieve a desired effect under specified standards and conditions. A capability is realised through combinations of ways and means. The ability of one or more resources to deliver a specified type of effect or a specified course of action. NOTE: The term “capability” has a number of different interpretations (especially in the military community). In NAF, the term is reserved for the specification of an ability to achieve an outcome. In that sense, it is dispositional—i.e., resources may possess a Capability even if they have never manifested that capability. The MODEM definition of Capability expresses this dispositional aspect from a set-theoretic point of view; “A Dispositional Property that is the set of all things that are capable of achieving a particular outcome”.	[60]
5	Knowledge integration is an organisational capability for creating novel combinations of different strands of knowledge, which have utility for solving organizational problems, from component knowledge sourced from within and beyond the organisation, and across time, and which derive from individual and group contributions, facilitated by both formal and social processes.	[61]
6	We defined organisational IT capabilities as complex bundles of IT-related resources, skills and knowledge, exercised through business processes, that enable firms to coordinate activities and make use of the IT assets to provide desired results.	[62]
7	An organisational capability refers to the ability of an organisation to perform a coordinated set of tasks, utilising organizational resources, for the purpose of achieving a particular end result.	[63]
8	An organisational capability is a high-level routine (or collection of routines) that, together with its implementing input flows, confers upon an organisation’s management a set of decision options for producing significant outputs of a particular type. NOTE: The term routine here means “repetitive pattern of activity”	[64]
9	A capability is the capacity for a team of resources to perform some task or activity	[65]
10	Thus, an operational capability enables a firm to perform an activity on an on-going basis using more or less the same techniques on the same scale to support existing products and services for the same customer population.	[66]

Table 2. Cont.

#	Definition	Source
11	Improvement capability is the ability to incrementally increase manufacturing performance using existing resources.	[67]
12	Dynamic IT capability is an IT unit's capacity to acquire, deploy, integrate, reconfigure, and transform the organisation's IT resources for the fulfilment of business objectives.	[68]
13	Measure of capacity and the ability of an entity (system, person or organisation) to achieve its objectives Note: Asset management capabilities include processes, resources, competences and technologies to enable the effective and efficient development and delivery of asset management plans and asset life activities, and their continual improvement.	[69]

Following retrieval, we conducted a content analysis of the identified definitions. Initially, this analysis revealed 50 distinct concepts embedded within the retrieved literature. After deduplication and decomposition of combined concepts (e.g., separating instances where “effect” was described as both an outcome and an enabler), we identified 36 unique conceptual elements (see Table 3). While some concepts appeared superficially related, careful examination of their contextual usage within the definitions revealed nuanced distinctions. For example, one definition characterised a capability as “an outcome or effect”, while another stated that it “enables us to achieve a desired effect”, highlighting the shared but distinct understanding of “effect” in these contexts. Therefore, the concept of “effect” is included twice.

Table 3. Cleaned dataset of 36 different concepts used in definitions.

Grouping 1	Grouping 2	Grouping 3	Grouping 4
specification of ability	(use of) features of a system	(use what) features of a system	benefit
(it is an) outcome	activity	(combine) ways and means	goal
(it is an) effect	(realised through) ways and means	resources	effect
ability	(facilitated by) process	component knowledge	course of action
organisational capability	task	skills	outcome
bundles of resources, skills and knowledge	acquire, deploy, integrate, reconfigure, and transform	inputs	solve organisational problems
routine		techniques	results
capacity		(include what) process	output
measure of capacity and ability		competences	support product or service
		technologies	increase performance
			objective

By examining the 36 concepts and their use within the context of the definitions, we grouped them in four logical groupings of concepts (see Table 3). These centre around the following topics:

Grouping 1: What the capability, as defined, is compared to and/or equivalent to?

Grouping 2: What the capability enables?

Grouping 3: What the capability consists of?

Grouping 4: What is the capability's purpose?

By analysing the data, we can see each of the four groupings is well represented within the definitions (see Figure 2). The second grouping is present in the least number of definitions—10 (76.9%), whilst the first and third are present in the most—12 definitions (92.3%). By examining how many of the four groupings are present in each of the definitions, we can see eight definitions include all four groupings of concepts (see Figure 3) four include three groupings, and one definition includes one grouping. The vast majority (twelve out of thirteen) include at least three of the groupings.

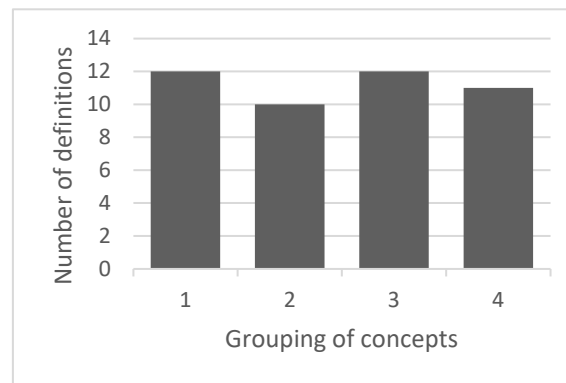


Figure 2. Number of definitions which include grouping of concepts 1, 2, 3, and 4.

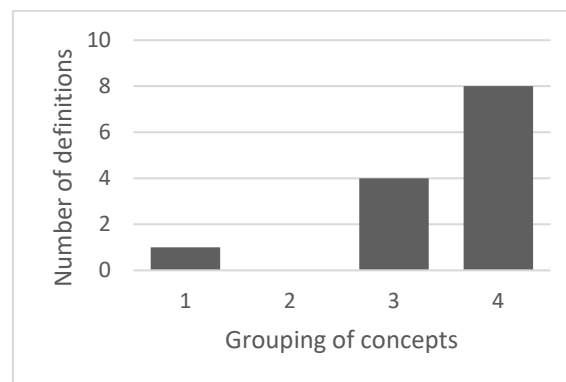


Figure 3. Number of definitions with 1, 2, 3 or 4 groupings of concepts included.

By removing definition one, which seems to be structured differently than the others, we can see the percentage of definitions which include grouping of concepts two rise from 76.9% to 83.3%, whilst the third grouping rises to 100% (see Figure 4).

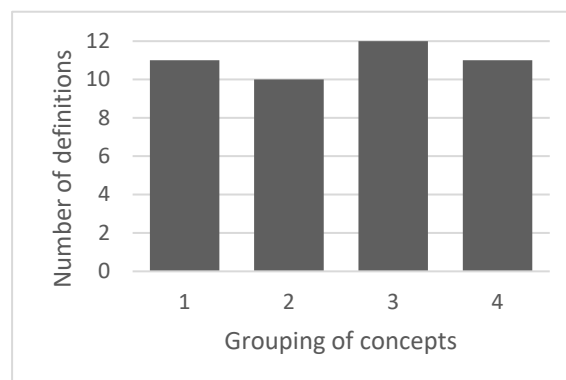


Figure 4. Number of definitions which include grouping of concepts 1, 2, 3, and 4 without definition 1.

The analysis shows the four groupings are well represented in all but one definition and can thus be considered appropriate to be used in further stages of the research.

The final step of the “List-group-label” methodology was to label previously identified groups. The labels needed to be generic and self-descriptive, so they would enable the next stage of the research, which was to have industry experts position them in the context of O&M within the infrastructure industry.

To express in the definitions what a specific capability is compared to or equivalent to, the concept of ability is used most often (see Figure 5). Ability refers to something which has been done or achieved before, under a specific set of conditions. However, when we talk about capabilities within an organisation, we also need to express their dispositional aspect (see “NOTE” section of the definition 4). Therefore, we believe the concept of ability is not adequate on its own. Other definitions use the concepts of capacity and specification of ability multiple times. The concept of capacity focuses on the maximum performance of an organisation when conducting a task, based on a given combination of resources and ideal conditions. Therefore, by focusing on capacity, performance can only be increased if we add more of the same resources, and in the same combination (quantity). Capacity, on the other hand, focuses on increasing the potential performance of an organisation when conducting a task, based on different resources, or a different combination of resources. Regardless, it is the ability which ultimately translates into performance. The concept “specification of ability” expresses both the aspect of ability, as well as the dispositional aspect (through “specification”). The concept from definition 13—measure of capacity and ability expresses a similar idea. Therefore, the last two are appropriate for our use.

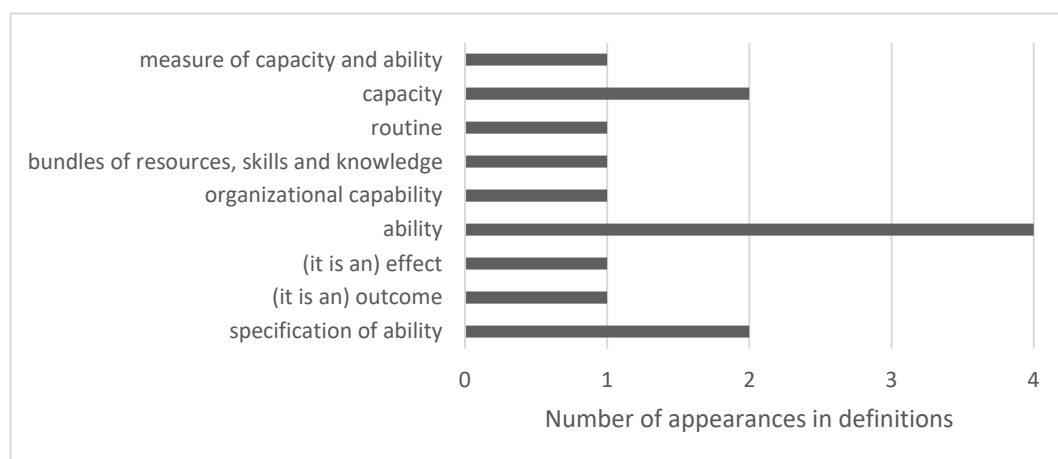


Figure 5. Number of times a concept from Grouping 1 appears in definitions.

To label the first group we chose a concept, which is superordinate to the ones above, and at the same time generic and self-descriptive—“Power”. All of the above concepts give the organisation the power to do something; therefore, we believe this is an appropriate label.

Capabilities enable performing of something, expressed in the definitions through the concepts of activity, task, and process, and in definition 12 in more detail through acquisition, deployment, integration, reconfiguration, and transformation. Ways and means referred to in definition 4 stand for activities and resources, respectively.

The chosen label for the second group was “Task”. We believe this is a better representation of what organisations do than the term “activity”, despite “activity” being used twice as many times in the definitions as “task” (see Figure 6). The concept of activity is superordinate to the concept task. Task is an activity with a purpose. In organisations all activity should have a purpose. Therefore, the concept of task was chosen.

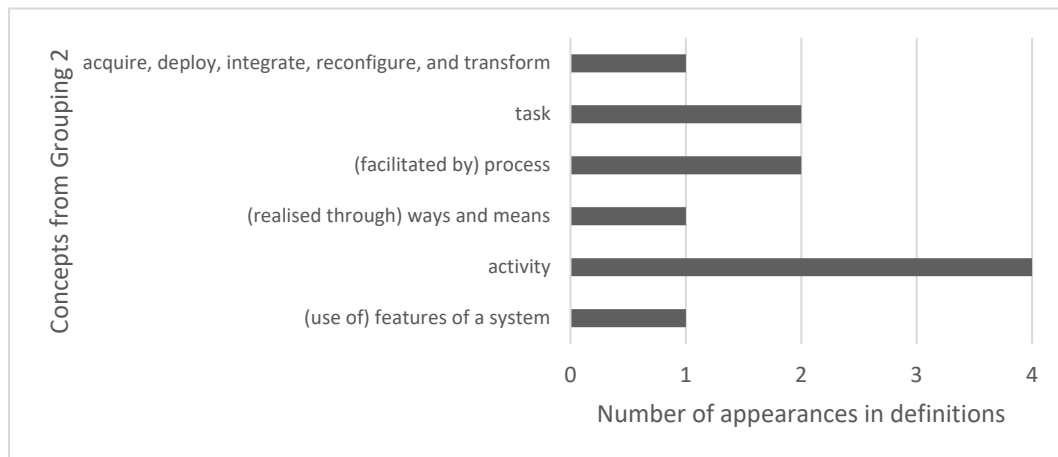


Figure 6. Number of times a concept from Grouping 2 appears in definitions.

Capabilities consist of resources, which are leveraged by tasks. Here, resources mean anything an organisation can acquire or develop itself, such as knowledge, skills, tools, processes, etc. Most of the definitions refer to the concept of resources, and some go into more detail, based on their context (see Figure 7).

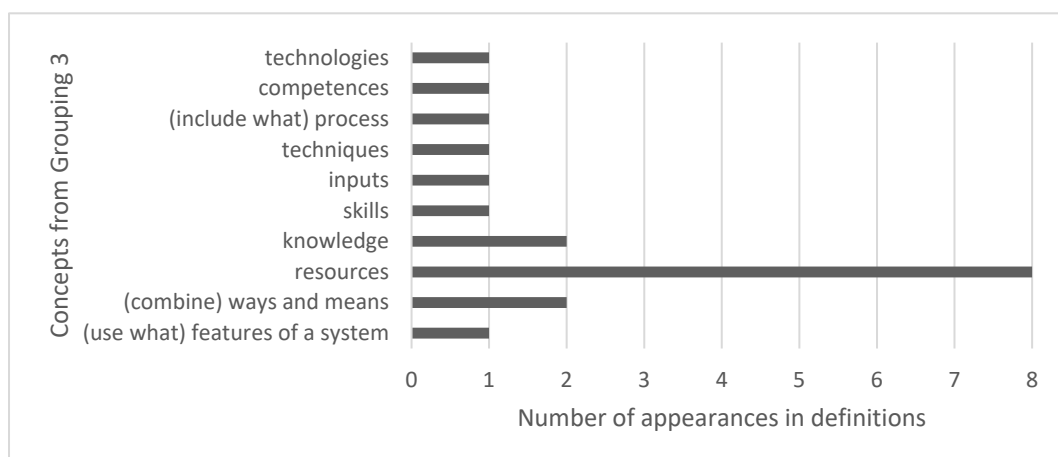


Figure 7. Number of times a concept from Grouping 3 appears in definitions.

For the third group, we chose the label “Resources”. The term “resources” is used in the majority of definitions, with the exceptions being context based, where actual resources are named.

The final group consists of concepts which express the purpose of the capability. Capabilities are acquired for a specific purpose, which contributes to the achievement of the overall goal of the organisation. The concepts of effect, result, and objective are used most often (see Figure 8).

The final group was labelled “Purpose”. The definition of purpose is “The reason for which something is done or created or for which something exists”. All capabilities are created with a specific purpose, which can be expressed through goals, outcomes, effects, etc., based on the organisation’s context. This purpose should be clearly defined and connected to the capability that will enable its achievement.

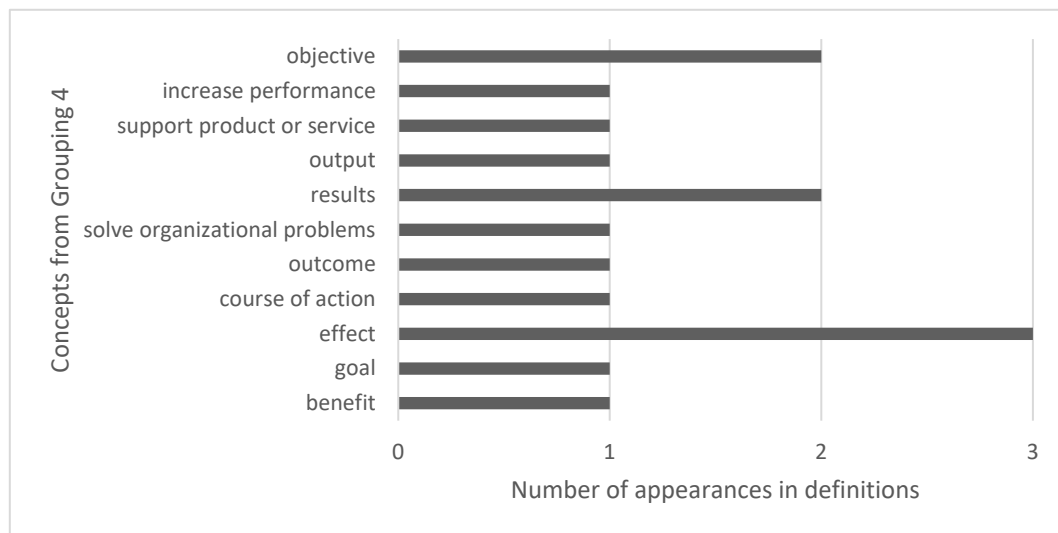


Figure 8. Number of times a concept from Grouping 4 appears in definitions.

In order to create a definition, we needed to combine the labelled concepts into a structured form which could be further investigated in the next stages of the research. Since the majority of the definitions we worked with above utilise a combination of concepts from at least three of the four identified groupings of concepts, as well as have a similar structure, we can conclude a generic formula for the definition of capability can be synthesised. Therefore, we synthesised the following formula:

$$C_D = C_E + C_T + C_C + C_P;$$

where

C_D ...definition of capability

C_E ...capability equivalent

C_T ...tasks enabled by capability

C_C ...components of capability

C_P ...purpose of capability

4.2. Adaptation of Concepts (Stage 2)

As part of the Stage 2 of our research, we conducted interviews with industry experts. To identify individuals of interest, we used purposive sampling (also known as authoritative sampling), a sampling technique used in cases where the specialty of an authority can select a more representative sample than other probability sampling methods [70] and also improve the quality of responses.

We used a purposive sampling approach by using the LinkedIn service and selecting the best professionals from thousands of potential candidates based on the criteria presented in Section 3.2, our expertise and our professional judgement. A personal and individualised approach to interview invitations combined with targeted selection significantly increased the likelihood of acceptance and resulted in a high response rate. We identified and invited a group of 14 industry professionals, 11 of whom responded to our interview request (see Table 4). As these are senior industry experts, most of them held multiple roles throughout their careers, some from multiple industries. We included their major roles in the table.

Table 4. Industries and number of years of experience of the interviewees.

#	Industry	Experience (Years)	Role Title	Region	Organisational Type
Interviewee 1	Nuclear, Roads, Rail	30–40	Senior Consultant/Technical information specialist	Europe/North America	Consulting
Interviewee 2	Manufacturing	15–20	Plant manager	Europe	Operator
Interviewee 3	Power	30–40	BIM manager	Europe	Operator
Interviewee 4	Government	20–30	Senior Consultant	Europe/Middle East	Software vendor
Interviewee 5	Manufacturing	15–20	Professor/Consultant	Europe	Academic
Interviewee 6	Oil & Gas	30–40	Director of consulting/Plant manager	North America/Europe	Consulting/Operator
Interviewee 7	Rail	40+	Head of Asset Management	Europe	Operator
Interviewee 8	Rail	15–20	Account Manager	Middle East	Software vendor
Interviewee 9	Roads	20–30	Data manager	Europe	Software vendor/Operator
Interviewee 10	Oil & Gas	15–20	Senior Consultant	North America/Middle East	Software vendor
Interviewee 11	Government	30–40	Senior Vice-President	North America	Software vendor

The sample of 11 experts was deemed sufficient based on several factors. First, we achieved our predetermined target of at least 10 interview partners. Second, the sample provided comprehensive coverage across key dimensions: multiple industries (nuclear, manufacturing, power, oil & gas, rail, roads, government), diverse role types (senior consultants, managers, directors, professors), varied organisational contexts (operators, consultants, software vendors, academics), and broad geographic representation (Europe, North America, Middle East). Third, thematic saturation was observed during the later interviews, with participants reinforcing concepts and themes identified in earlier interviews rather than introducing fundamentally new perspectives. The depth of expertise represented—with most participants having 15–40+ years of experience in senior positions—ensured rich, authoritative insights that compensated for the relatively focused sample size.

Details of the interviewees are presented in Table 4.

The interviews were conducted from late October to the end of November of 2022. Due to the majority of the interviewees being globally dispersed, the interviews were done remotely, via Microsoft Teams. The duration of each interview in large depended on the interviewee, and their willingness to explain their ideas, concepts, experiences, and practices in a lot or a little detail, but, in general, they lasted between 45 and 60 min, which was sufficient to get the answers we needed.

The interviews were conducted in a semi-structured approach. This means we had pre-prepared questions and sub-questions (see Appendix A), which, during the interviews and depending on the interviewees' answers, we followed up with further questions, which were not pre-prepared. The pre-prepared questions were open-ended with the aim of having the interviewees do the majority of talking and potentially opening interesting and unexpected venues for conversation. In some cases, when we felt the question was not getting us further along, we utilised a scenario approach where we described an imaginary but plausible scenario and asked the interviewee how they would approach it.

The first part of the interviews was focused on capabilities within O&M organisations, their definition for them, and how they build them. The term “capability” proved to be widely used, however its meaning differed based on the context. When asking the question whether organisations have a definition for O&M capabilities the universal answer was no.

When asking whether organisations have a defined set of O&M capabilities, the answer in most cases was no. In one case it was yes, but they could not produce a list or any examples.

The second part of the interviews was focused on placing the generic key concepts identified as part of the stage 1 of this research, within O&M of infrastructure assets. All interviewees agreed the identified key concepts are relevant to the O&M discipline, however before explaining the term “power” within the capability context, they had trouble understanding its exact fit within the domain. Therefore, whilst this term is generic, it is not self-descriptive enough to be included in the definition on its own. Other three key concepts were understood without additional explanation.

Our qualitative analysis used a thematic approach, building on concepts initially identified in Stage 1 of the research. These preliminary concepts served as guiding prompts during interviews, allowing us to test their relevance and refine our understanding through participant feedback. The coding process was conducted manually, without dedicated software, enabling close and iterative engagement with the interview data.

The interviews exposed that the power an acquired capability brings to an organisation is often not optimal, due to various reasons. It starts with the identification and acquisition of the capability, as this process is often influenced by office politics and strength of individuals, which influence the choosing of the capability, rather than it being an objective process, led by organisation’s overall and integrated goals. This weakness is often exposed when individuals leave the organisation. The aspect of capability acquisition through the supply chain was also mentioned. The work the contractors do in the O&M industry is often driven by money and legislation, and not the impact on the infrastructure assets the owner of those assets desires.

Acquired capabilities enable the organisation to perform tasks. These can be at different levels, from strategic to tactical, and are done daily. A number of capabilities may be needed to perform a task. When capabilities are acquired from the supply chain, tasks are controlled by the contracts and driven by money and legislation. Tasks require a number of inputs to be completed successfully, such as information, people, machines, process, etc., i.e., organisation’s resources. Tasks need to be relevant, as organisations frequently maintain established practices due to organisational inertia. The tasks performed by an organisation operating and maintaining infrastructure assets should lead to reliable performance of infrastructure assets, which enable the users to utilise said assets as planned.

Interviewees talked about resources, such as knowledge, skills, equipment, raw materials, processes, standards and others. These resources can be grouped into a number of groups, such as people, organisation, tools, facilities, financial assets, data, etc. Some combination of these enables the performing of tasks. The generic people, process, and technologies was mentioned by a number of interviewees.

Discussions about the purpose the capabilities are acquired for mentioned aspects, such as reliability of the asset, the improvement of the way tasks are done currently, the achievement of outcomes and goals, increase in quality, reduction in downtime and increase in uptime of assets, increase in revenue and cost reduction, efficiencies, etc. Continuous measurement of how well a capability is achieving its purpose and accountability for results were considered very important. These go hand in hand with clearly defined KPIs, but also enablement of individuals to be able to impact these meaningfully. Understanding and communicating why something must be done in a certain way were echoed by a number of interviewees. Individuals’ impact is often affected by procedures, which can be too restrictive. Capabilities are acquired for a purpose, valid at the time of the acquisition. However, as time progresses and the organisation’s goals change, that purpose might not be valid anymore, and thus the need for that capability might not exist anymore. This needs to be recognised and the capability retired.

Based on the discussions with industry experts we decided there is a need to tailor two of the four chosen terms to relate to the O&M of infrastructure assets more closely. We changed the term “power” to “high-level specification of ability”, same as in definitions 1, 4, and similar to 13 (see Table 2), as we believe this explains the concept of capability better. We also changed the term “purpose” for a specific purpose of O&M—“reliability of infrastructure assets”, i.e., “asset reliability refers to the ability of a physical asset to maintain its functionality and perform its intended function over time”.

4.3. Findings (Stage 3)

To define the concept of O&M capability we utilised the formula we defined in Stage 1, which served as the structure, and the key concepts tailored in Stage 2, which provided the content.

The formula provided the following definition: *“Operations and Maintenance capability is a high-level specification of an organisation’s ability to perform the tasks needed to ensure the reliability of infrastructure assets through the utilisation of organisation’s resources.”*

Firstly, we validated the proposed definition (see Table 5) against the eight rules for writing formal conceptual definitions [56]. These rules are:

1. The concept must be defined using primitive and derived terms to determine that the terms are assumed to be known by the reader.
2. Formal conceptual definitions should not violate the uniqueness virtue of “good” theory.
3. ... definitions should include only unambiguous and non-vague terms.
4. ... definitions should use as few terms as possible to convey the essence of the concept.
5. ... definition should be as consistent as possible inside the generic academic field as well within the theory.
6. New formal conceptual definitions should not expand current definitions to make them less precise and broader.
7. ... definitions should not contain new hypotheses.
8. Empirical tests validity should be performed only after the formal conceptual definition passes the first seven rules.

Table 5. Validation of the proposed definition against the eight rules for writing formal conceptual definitions.

Rule	Conformance	Comment
Rule 1	YES	Definiens can be inserted in place of definiendum without changing the sentence’s meaning.
Rule 2	YES	Definiens are differentiated from other seemingly similar terms.
Rule 3	YES	The definition is made unambiguous and non-vague through the use of modifiers.
Rule 4	YES	The definition was built to use the least number of terms to convey the meaning of the concept without violating Rule 3.
Rule 5	YES	The definition is consistent
Rule 6	YES	The definition does not expand current definitions.
Rule 7	YES	The definition does not contain new hypotheses
Rule 8	YES	The definition conforms with the previous Rules and is therefore ready for empirical tests

Secondly, we validated the definition through a survey sent to the 11 interviewees. They had the possibility of agreeing with it, disagreeing with it, and adding a comment. We received 10 replies, all of which have agreed with the definition. Four of them included a comment suggesting a potential change (see Table 6).

Table 6. The results of the survey.

#	Agree (YES/NO)	Comment	Response
Interviewee 1	YES	/	
Interviewee 2	YES	/	
Interviewee 3	YES	Challenged the inclusion of the term “specification”	The term “specification” is essential to express the dispositional aspect of the capability. Through ability, we express the actual performance, whilst capability expresses the potential performance.
Interviewee 4	YES	/	
Interviewee 5			
Interviewee 6	YES	/	
Interviewee 7	YES	It should include to term “define” and not just “perform”	We believe the term “define” is implied through “the tasks needed to ensure the reliability”, as in if you don’t define the right tasks, reliability can’t be ensured. However, we agree that implication might not be the best mechanism to ensure compliance or even awareness, therefore we have decided to add the suggestion to the definition.
Interviewee 8	YES	/	
Interviewee 9	YES	How does it incorporate governance?	Governance is incorporated as one of the tasks mentioned in the definition.
Interviewee 10	YES	/	
Interviewee 11	YES	Could leave out parts about resources and “high-level specification”, to simplify it and increase its effectiveness	Most of the definitions in the field include three or four of the elements defined in the formula. We believe leaving out parts could impact the clarity of the definition and differentiation from other similar concepts. Therefore, we decided against taking out the suggested parts.

5. Discussion

The aim of our work was to develop a definition of the concept of O&M capability. Our synthesis allowed us to develop a comprehensive and robust framework (formula) that builds on existing definitions and perspectives from multiple fields. We believe we have captured the essence of the concept and increased its accuracy, while providing a structured approach for future definitions.

5.1. Positioning Within Existing Capability Frameworks

While existing frameworks offer valuable organisational perspectives, they have limitations when applied specifically to O&M contexts. The Resource-Based View (RBV) primarily addresses competitive strategy rather than operational reliability requirements. Dynamic capabilities focus on adaptation and transformation, which, although relevant, do not capture the core operational stability required for infrastructure asset reliability. ISO

55000's [71] asset management capabilities are broadly defined across entire asset lifecycles, lacking the operational specificity necessary for day-to-day O&M activities.

Our framework addresses these gaps by providing an O&M-specific conceptualisation. Unlike RBV's competitive focus, our framework centres on reliability outcomes essential for infrastructure assets. Unlike the dynamic capabilities' emphasis on change, our framework emphasises consistent performance delivery. Unlike ISO 55000's lifecycle breadth, our framework specifically targets O&M activities. The framework's contribution lies not in replacing these established theories but in bridging the gap between general capability concepts and the specific requirements of infrastructure O&M. By grounding capability definition in operational tasks and reliability outcomes, the framework provides practitioners with actionable conceptual clarity that existing frameworks do not deliver for O&M contexts.

5.2. Methodological Contributions

Although the definitions from different fields and industries may appear different at first glance in terms of the key concepts used, our approach revealed the underlying common thread that links them all together. This contributes to the transcendence of the formula developed, as is often the case with complex concepts found in multiple fields.

By utilising industry experts to discuss the key concepts of our developed formula and placing them in the appropriate context of O&M, we also anchored them in practice. Our discussions showed that some of our original key concepts were too vague and could easily be misunderstood. Through their insights, we were able to understand the current state of thinking in the industry and how our formula should be tailored to O&M. This iterative refinement process—from generic concepts to O&M-specific terminology—demonstrates the value of expert validation in concept development.

5.3. Balancing Comprehensiveness and Simplicity

Balancing the comprehensiveness of the definition with its simplicity was one of the main challenges. The inclusion of the four key concepts in the definition is crucial for understanding the concept of O&M capability. This was challenged in our interactions with industry experts to increase simplicity; however, we felt simplification might compromise its integrity. We believe we achieved this balance by retaining conceptual precision while using terminology familiar to O&M practitioners.

5.4. Limitations and Generalizability

Several potential biases should be acknowledged. The LinkedIn-based recruitment may have introduced bias toward professionals with strong online presence and those comfortable with digital networking platforms. The sample exhibits geographic concentration in Europe and North America, potentially limiting insights from other regions with different infrastructure contexts and approaches. Additionally, the focus on senior-level professionals may have emphasised strategic perspectives while potentially underrepresenting operational-level insights. The predominance of large organisations and established consulting firms may have limited perspectives from smaller operators or emerging market contexts. Despite these limitations, the purposive sampling approach was appropriate for capturing authoritative expertise on infrastructure asset management practices across diverse industry contexts.

While our framework emerged from diverse infrastructure sectors, questions remain about its direct applicability across all smart city contexts without adaptation. The definition may require sector-specific refinement when applied to highly specialised domains such as digital infrastructure or integrated IoT systems that differ substantially from traditional physical assets. While the research may be limited in terms of interview quantity, we

prioritised quality. However, the views of the interviewees, whilst globally dispersed, still do not represent a complete global dataset. As they come from multiple industries, industry-based variations may be required, though the formula we proposed may still support that adaptation.

We believe our research achieved its objective of synthesising a definition of O&M capability that may benefit both practitioners and academia.

6. Conclusions

Effective O&M capabilities are critical for the reliable functioning of smart infrastructure and transportation systems in smart cities. However, despite the concept of capabilities being widely used in the fields of O&M, it is inconsistently defined and applied, which creates barriers to standardisation and interoperability. Our research has shown that a definition of the term “operations and maintenance capability” is clearly lacking. This is a fundamental shortcoming which hinders the development of robust O&M systems, essential for sustainable smart cities.

In our research, we found a number of definitions of capability in other areas of study and approaches to synthesising a definition. Through the approach we took, we were able to identify four fundamental components of a capability definition. These components were formulated into a structured capability definition with generic terms applicable across various smart city infrastructure contexts. This formula can also help other industries define this term. To tailor the definition to the O&M field, we conducted semi-structured interviews with leading industry experts. In the interviews, we discussed the background and relevance to the O&M industry for each of the four terms. Based on the discussions, we adapted two of the four assigned terms and defined O&M capabilities in the final stage of our research.

We believe the definition will be fundamental to future work for advancing smart city O&M practices, particularly in the areas of data interoperability, predictive maintenance systems, and integrated mobility solutions. The definition enables consistent communication among stakeholders including technology providers, regulatory bodies, and urban planners, supporting the development of standardised approaches to smart mobility. This could stimulate discussion around the definition itself, leading to possible improvements. Future research should leverage the foundation created by the definition of O&M capabilities to develop standardised O&M capability models for specific smart city applications, including cooperative intelligent transportation systems (C-ITSs), mobility as a service (MaaS) platforms, and integrated urban mobility solutions. This work will show us how robust our definition is and whether changes are needed while contributing to the broader goals of sustainable, efficient smart city operations. Additionally, the framework’s (formula) integration with emerging ICT standards and regulatory frameworks represents a crucial next step in bridging the gap between research and practical implementation in smart mobility systems.

The establishment of our four-component framework provides concrete operational guidance for practitioners. Organisations can operationalize this definition by (1) specifying their O&M abilities through systematic capability assessments, (2) defining reliability-focused tasks aligned with asset requirements, (3) mapping resource allocation to capability needs, and (4) establishing reliability metrics to measure capability effectiveness. This structured approach enables standardised capability development while supporting the broader goals of interoperable and resilient smart city O&M solutions.

Future research should focus on developing sector-specific applications of this framework and validating its effectiveness across different urban infrastructure contexts. It would also benefit from incorporating broader perspectives through increased engagement

with digital infrastructure stakeholders, such as IoT providers and smart city platform developers, to ensure the definition remains adaptable to evolving software-defined and data-driven infrastructure systems that are becoming increasingly integral to smart cities.

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Institutional Review Board Statement: This research was conducted in accordance with the ethical principles outlined in the Declaration of Helsinki and applicable national and institutional guidelines for research involving human participants, specifically the Guidelines for Ethical Conduct Involving People and Personal Data Protection at the University of Ljubljana. The researchers followed best practices in research ethics, including obtaining informed consent from all participants where applicable, ensuring participant confidentiality, and safeguarding data in compliance with relevant privacy regulations. At the time the study commenced, the research activities were outside the scope of mandatory ethics committee review, as they involved only non-sensitive, anonymized data and posed no more than minimal risk to participants.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study, with participants voluntarily agreeing to participate after being informed of the research purpose and scope.

Data Availability Statement: The original contributions presented in this study are included in the article. The interview guide is included in Appendix A. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A Interview Guide

Qualitative interview introduction

- Length: 45–60 min
- Primary goal:
 - to gather insights,
 - to validate key concepts for the O&M disciplines and
 - discuss them in the context of O&M.

Informed consent

- Procedure:
 - 1:1. interview
- Confidentiality:
 - no additional profiling,
 - (a) anonymous data storage in compliance with relevant privacy regulations.

1. Question: Would you like to participate in this interview?

Verbal Consent was obtained from the study participant

Verbal Consent was NOT obtained from the study participant

Interview

2. Question: What does the term “organisational capabilities” (OC) mean to you?
 - a. How do you employ them in your organisation?

3. Question: How do you acquire OCs in your organisation?
 - a. Is there a formal way? Is it standardised?
 - b. Who and how decides on what OC will get acquired?
 - c. Who advises what will get acquired?
 - d. Is there a gap/misunderstanding about requirements for OCs between different hierarchical levels, or horizontally?
 - i. Do you collaborate with other departments?
 - ii. Is each department a small company?
 - e. Do you employ scenarios, when deciding what to acquire?
4. Question: Do you define goals for each capability before you acquire it?
 - a. Do you and how do you measure the success of the capability, i.e., how well you are achieving the goals?
 - i. What happens if it doesn't achieve it?
5. Question: How do you decide a certain capability is surplus and how do you remove it?
6. Question: Imagine you have a capability which is good enough already, and a new piece of technology comes along, which promises even better returns—do you upgrade it? Or does it get put in the plan for future?
7. Question: Is there a running plan/a schedule which lists all capability acquisitions to happen in the future?
8. Question: What do you think of when you hear the term “Power” in the O&M context?
9. Question: What do you think of when you hear the term “Task” in the O&M context?
10. Question: What do you think of when you hear the term “Resources” in the O&M context?
11. Question: What do you think of when you hear the term “Outcomes” in the O&M context?

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