Capabilities in Systems Engineering: An Overview

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Abstract. The concept of capability has been deemed relevant over the years, which can be attested by its adoption in varied domains. It is an abstract concept, but simple to understand by business stakeholders and yet capable of making the bridge to technical aspects. Capabilities seem to bear similarities with services, namely their low coupling and high cohesion. However, the concepts are different since the concept of service seems to rest between that of capability and those directly related to the implementation. Nonetheless, the articulation of the concept of capability with the concept of service can be used to promote business/IT alignment, since both concepts can be used to bridge different conceptual layers of an enterprise architecture. This work offers an overview of the different uses of this concept, its usefulness, and its relation to the concept of service.

Key words: capability, service, alignment, information systems, systems engineering, strategic management, economics

1 Introduction

The concept of capability can be defined as "the quality or state of being capable" [19] or "the power or ability to do something" [39]. Although simple, it is a powerful concept, as it can be used to provide an abstract, high-level view of a product, system, or even organizations, offering new ways of dealing with complexity. As such, it has been widely adopted in many areas.

In economics and strategic management, capabilities are a part of the resource-based view of the organization [11, 2], which built upon the idea that firms could have the same resource inputs available but they could differ on the capability to use those resources in the most productive way [27]. In that sense, capabilities can be seen as a factor of competitive advantage which differentiates firms [9], functioning as a means for organizations to adapt better than others to changing environmental conditions [5, 22]. The concept of capability involves routines that are executed by the organization in a repeatable and often non-conscious way [22].

In the area of system engineering, capabilities are seen as a core concept [20]. Particularly in the military field, a capability is seen as the ability to achieve

a determined military objective [37], requiring a combination of people, process and material [24]. In general, this notion is considered particularly relevant for the engineering of complex systems-of-systems (SoS), which relies on the combination of different systems for achieving a particular capability [18, 4].

In software engineering, the first capability maturity model (CMM) was developed with sponsorship from the US Department of Defense with the aim of assessing the capability of software contractors [12, 13]. For that purpose, it considers processes as capabilities, thus defining how to assess specific qualities of software engineering processes, providing a way to understand the current state of potentially complex software systems. The CMM has ever since been evolving and integrating several other models. Nowadays, it covers acquisition, development and delivery processes [6, 7, 8].

The concept was also embraced by the information systems field, namely by the Enterprise Architecture (EA) domain through its use, for example, on the US Department of Defense Architecture Framework (DoDAF) [38] and the UK Ministry of Defense Architecture Framework (MODAF) [36]. It has since then been also adopted by The Open Group Architecture Framework (TOGAF), a generic enterprise architecture framework where it is an integral part of the architectural practices described in its specification [35].

In the field of organizational design and engineering, which advocates the combination of organization theory and engineering practice in order to create computer-based artifacts that sustain economically relevant knowledge, capabilities and their underlying routines also are considered concepts of major research importance [17]. They are considered to provide a means of observing the drivers that underlie change in organizations and, according to that, steer the organization in the right direction.

In all, capabilities can be seen as a way of linking stakeholder intentions to the properties of a system [28], which obviously are closely related to the concept of service, making the bridge between intentions and actual implementation. It is a concept which can be linked directly into the drivers and motivation, being stable in face of change, similarly to the concept of service, albeit at a different abstraction level. This work offers an overview of the different uses of this important concept and its usefulness, and its relation to the concept of service.

This work is organized as follows. Section 2 provides an historical account of the usage of the concept in the areas of economics and strategic management, pioneers in the usage of the concept. Section 3 provides an historical account of the usage of the concept in the areas of systems and software engineering, which pioneered on the usage of the concept in systems where the technical aspect is evident. Section 4 provides an account of the usage of the concept in the area of information systems, which evidently was influenced by its usage in systems engineering. Section 5 provides a summary of the different definitions of capability provided in the aforementioned areas. Section 6 describes the relationships existing between the concept of capability and the concept of service, arguing

for the importance of the joint use of the two concepts in service design and engineering. Finally, section 7 concludes this work.

2 On the Concept of Capability in Economics and Strategic Management

The concept of capability has been adopted in several areas of knowledge. The concept of *organizational capability* has been used for many years in economics and strategic management essentially to explain competitive advantage. Early mentions of the term, although not reified, include the ones by Penrose [27], in 1959, which indicated that the differences between firms could be explained by differences in the capabilities to deploy resources that were available to all firms, and by Richardson [30], in 1972, which pointed that those differences were explained by the fact that firms tend to specialize in activities for which their capabilities offer competitive advantage.

In their 1973 publication, Nelson and Winter introduced the idea that competitive advantage comes both from the internal and external search processes for enhanced production capabilities and the "*natural selection*" processes that influence the growth and contraction of organizations, resulting as an indirect consequence of the search [21]. As described later by the authors, the usage of the term *capability* in this work came from the involvement of the authors in the military field at the time, and not directly from the works cited above [40]. The same authors later presented their evolutionary theory that described organizational capabilities as consisting of the ability to "perform and sustain a set of routines" [22]. Those routines are "habitual reactions" that involve coordination among the actors of the organization and the usage of skills, organization and technology to respond to the demands of the environment. Routines can even be considered the building blocks of capabilities, since for a set of activities and associated resources and skills to be considered a capability, there is a need for repeatability [9]. In order to survive, organization should engage on search operations which involve the evaluation of the current situation and changes to the organizational capabilities, if needed [22]. Chandler described organizational capabilities as the "collective physical facilities and human skills", "carefully coordinated and integrated", as a means of achieving economies of scale and scope, highlighting their importance in the evolution of capitalism [5].

The concept of organizational capability promoted by Nelson and Winter was highly influential for the development of the concept of dynamic capability, initially developed by Teece and Pisano, in 1994 [33]. The former notion of capabilities can explain why firms attain competitive advantage in a determined market, but it fails to explain why some firms can adapt to highly disruptive changes in the environment prompted by technological change, critical timings, or even change in markets and competition [34]. Dynamic capabilities involve "reconfiguring the internal and external organizational skills, resources, and functional competences to match the requirements of a changing environment" [34].

The same work also describes the existence of factors that can be used to assess the distinctive capabilities of an organization (i.e., those which cannot be easily replicated by others), and that are classified in three categories: processes (i.e., the routines or other activities), positions (i.e., current technological infrastructure, intellectual property, customers, relation with suppliers, etc.), and paths (i.e., strategic alternatives available to the organization). The relationship between these three categories is explained by the fact that the essence of capabilities lies in the processes of the organization. However, competitive advantage is driven or constrained by the positioning of the internal and external assets of the organization and by the evolutionary path that the firm has chosen to adopt. In the words of the authors, "what a firm can do and where it can go are thus rather constrained by its positions and paths". Those factors can only deliver competitive advantage if the capabilities are based on a collection of routines, skills, and assets that are difficult to imitate.

The work in [10], published in 2000, argues that dynamic capabilities are not themselves sufficient for attaining competitive advantage, since their functionality can be duplicated by organizations. However, competitive advantage lies on the resource configurations deployed by those capabilities. Additionally, dynamic capabilities are important for achieving short-term advantages through reconfiguration of the resources in order to make the most out of an opportunity. In order to be effective, dynamic capabilities often need to rely on new knowledge, which might involve experimental activities, such as prototyping, real-time information, and experimentation. The evolution of these capabilities is guided by well-known learning mechanisms. Product development routines, strategic decision making, resource allocation routines, knowledge creation routines, alliance and acquisition routines are given examples of dynamic capabilities.

In order to explain the evolution of capabilities, the work in [11], published in 2003, describes a generic capability life cycle framework that can be applied to any type of organizational setting. The framework divides the life cycle of a capability in three plus six stages. The three first stages are: the *founding* stage, which marks the "birth" of a capability; the *development* stage, which represents the building up of the capability; and the *maturity* stage, which marks the ending of the capability building. The *maturity* stage can then be followed by any of the following six stages in different combinations or orders (or even simultaneously in some cases): *retirement*, which marks the death of a capability; *retrenchment*, which depicts the gradual decline of a capability; *renewal*, which depicts the improvement of the level of a capability, and which might involve minor or major modifications to a capability; *replication*, which depicts the transfer of a capability into a new market; *redeployment*, which represents another type of capability transfer, this time for producing a different but closely related result; and *recombination*, which aims to improve a capability through the combination of existing capabilities.

3 On the Concept of Capability in Systems and Software Engineering

The International Council on Systems Engineering (INCOSE)[1] defines Systems Engineering as being "an interdisciplinary approach and means to enable the realization of successful systems", focusing in the whole life cycle of the system, from the definition of stakeholders' requirements to the dismantlement of the system, considering the business and technical needs of customers in order to provide a quality product [31]. One of the origins of systems engineering is arguably the military field [31]. As such, much of the terminology used in the domain has been adopted from that origin, including the concept of (military) capability. A *military capability* is defined as the ability to achieve a determined military objective [37], requiring a combination of people, process and material [24].

It was precisely on the military field that the first capability maturity models (CMM) appeared. The Software Engineering Institution (SEI) of the Carnegie Mellon University, funded by the U.S. Department of Defense produced the first capability maturity model for assessing software engineering processes, in 1987 [12, 13]. The main purpose of the CMM is to achieve a controlled and measurable software engineering practice that can be continuously improved [12]. In this specification, software engineering capability is divided in three areas: organization and resource management, software engineering process and its management, and tools and technology. Despite the fact that this segmentation seems to match the triplet of people, process and material, the term *process* is used throughout the specification as a synonym for capability.

CMM was launched in its 1.0 version in 1991 [25], and version 1.1 came out in 1993 [26], incorporating the feedback from the software engineering community. Soon, capability maturity models began being adopted by other areas, including the more general area of systems engineering, with the purpose of improving its processes. In the *A Systems Engineering Capability Maturity Model, Version 1.0*, issued in 1994, a capability is defined as a "measure of the system's ability to achieve the mission objectives, given that the system is dependable and suitable" and as a "systems engineering metric" [3]. Based on this work, the Electronic Industries Alliance[2] published standard EIA-731.1 - Systems Engineering Capability Model, which described capability as involving the attributes of people, technology, and process [1]. In an effort to unify capability maturity models, the SEI published the Capability Maturity Model Integration (CMMI) as a unifying model for three different process areas: acquisition, development, and services [6, 7, 8].

It was also in the military field that the idea that capabilities could be used as essential building blocks in engineering efforts was formed [24]. *Capability engineering* is a process which supports *capability management* throughout the life cycle of a capability. *Capability management* aims to manage capabilities

[1] http://www.incose.org/
[2] Already extinct.

through an integrating framework consisting of three inter-related functions: *capability generation*, which refers to the conception, development, planning, acquisition and management of a capability; *capability sustainment*, which refers to the sustainability of a capability at an appropriate level of readiness, for a determined time horizon; and *capability employment*, which refers to the planning for and conducting military operations which involve the use of the capability.

The concept of capability was also adopted in IBM's Rational Method Composer[3], more precisely the concept of capability pattern. The Method Composer allows the customization of the Rational Unified Process (RUP) for software engineering. RUP provides several disciplines which are collections of tasks which can be applied during the life cycle of a system. These tasks can be combined into workflows. A capability pattern is a reusable process which can be applied at any stage of the life cycle and prescribes a work breakdown structure (the workflow), the team allocated to the activities, and the work products produced from the activities.

4 On the Concept of Capability in Information Systems

An information system can be defined as "an information processing system, together with the associated organizational resources such as human, technical, and financial resources, that provides and distributes information" [15], a definition which in some sense presents some similarities with that of capability. One of the main research topics in information systems is *enterprise architecture*.

Enterprise Architecture (EA) is a holistic approach to systems architecture with the purposes of modeling the role of information systems and technology on the organization, aligning the enterprise-wide concepts, aligning the business processes and information with the information systems, planning for change, and providing self-awareness to the organization [32]. Despite the fact that it was first created with a more traditional company setting in mind, its practices where also adopted by the military field with the surfacing of two well known enterprise architecture frameworks: the US Department of Defense Architecture Framework (DoDAF) [38] and the UK Ministry of Defense Architecture Framework (MODAF) [36].

Both frameworks adopt the concept of capability, and explicitly model it through its inclusion on the meta-model and on the viewpoints provided by the framework. DoDAF defines capability as being an ability to achieve a desired effect under specified conditions through the combination of activities and resources [38]. In MoDAF, a capability is defined as a a classification of some ability that the enterprise possesses, and that it can be specified wether the enterprise is able to achieve it or not [36]. Capabilities in MoDAF can be represented through a composite structure entitled *capability configuration*, which us defined as "a set of artefacts or an organization configured to provide a capability", and involves physical, human, and software resources and the interactions between them.

[3] http://www-01.ibm.com/software/awdtools/rmc/

Table 1. The concept of capability in the analyzed domains

Domain	Definition	Source
Strategic Management	The ability to perform and sustain a set of routines, involving coordination among the actors of the organization and the usage of skills, organization and technology to respond to the demands of the environment.	[22]
	The collective physical facilities and human skills, carefully coordinated and integrated, as a means of achieving economies of scale and scope.	[5]
	The essence of capabilities lies in the processes of the organization, driven or constrained by the positioning of the internal and external assets of the organization and by the evolutionary path that the firm has chosen to adopt.	[34]
Systems and Software Engineering	A (military) capability is defined as the ability to achieve a determined military objective, requiring a combination of people, process and material.	[37, 24]
	Capability is divided in three areas: organization and resource management, software engineering process and its management, and tools and technology.	[12]
	A measure of the system's ability to achieve the mission objectives, given that the system is dependable and suitable.	[3]
	Involves the attributes of people, technology, and process.	[1]
Information Systems	An ability to achieve a desired effect under specified conditions through the combination of activities and resources.	[38]
	An ability that the enterprise possesses, and that it can be specified whether the enterprise is able to achieve it or not. Its configuration involves physical, human, and software resources and the interactions between them.	[36]
	An ability that an organization, person, or system possesses, typically requiring a combination of organization, people, processes, and technology.	[35]

The concept of capability is also making its cross to general enterprise architecture approaches. The Open Group Architecture Framework (TOGAF), a generic enterprise architecture framework where it is an integral part of the architectural practices described in its specification [35]. The concept is a part of the meta-model and a capability-based planning for business is included as one of the techniques provided by the specification. TOGAF defines capability as "an ability that an organization, person, or system possesses", and that it typically "requires a combination of organization, people, processes, and technology" [35].

5 Consolidation of Definitions

Based on the descriptions provided in the previous sections, Table 1 describes the different definitions for capability stemming from different areas of knowledge. It is clear that a capability is delivered by a determined configuration of

the organization's resources and it is influenced (driven or constrained) by the surrounding environment. In that sense, the definition provided in [34] provides a sound and broad characterization of what constitutes a capability, and that is compatible with the other listed definitions. In detail, the factors that can be used to assess the instinctive capabilities of an organization are (i.e., those which cannot be easily replicated by others):

- processes (i.e., the routines or other activities)
- positions (i.e., current technological infrastructure, intellectual property, customers, relation with suppliers, etc.)
- paths (i.e., strategic alternatives available to the organization).

The relationship between these three categories is explained by the fact that the essence of capabilities lies in the processes of the organization. However, competitive advantage is driven or constrained by the positioning of the internal and external assets of the organization and by the evolutionary path that the firm has chosen to adopt. In the words of the authors, "what a firm can do and where it can go are thus rather constrained by its positions and paths". Those factors can only deliver competitive advantage if the capabilities are based on a collection of routines, skills, and assets that are difficult to imitate.

6 On the Concept of Capability and Services

The relationship between capabilities and services seems rather obvious, since capabilities aim to bridge stakeholders intentions to the properties of a system [28]. In fact, capabilities can be seen as functional abstractions decoupled from implementation, and exhibit properties similar to those possessed by services: low-coupling and high cohesion [29]. Given this, it becomes important to differentiate the concept of capability from that of service, something that is already done in enterprise architecture frameworks, although in some cases without providing a clear relationship between the two concepts (e.g., TOGAF), and on relevant service-related modeling languages, which relate the two concepts but do not provide a full enterprise model.

Concerning service-related modeling languages, two examples of such languages making use of the concept are BSDL and SoaML, the former more related to the business realm and the last more related to technical aspects. The Business Service Description Language (BSDL) has the purpose of describing business services from a pure business perspective, addressing specifically their decomposition and non-functional properties [16]. It aims to close the gap existing between more strategy and goal description languages and operational service description languages, and to model both functional and non-functional concepts related to business services. The concept of capability is modeled as a functional concept, representing a function that is performed by a business service. The SoaML modeling language is another example of the inclusion of the concept of capability in the meta-model of the language. The usage of this

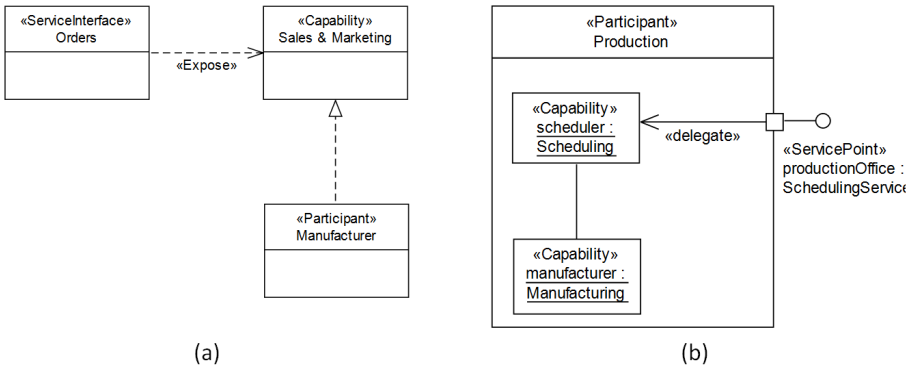

Fig. 1. Capabilities in SoaML

concept allows the expression of service architectures in terms of the logical capabilities of the services in a way that is agnostic to participants in the architecture, identifying a set of functions or resources that a service might provide or the abilities that are needed in order to provide a service [23]. Figure 1.(a) depicts the capabilities that a service interface provides, and Figure 1.(b) depicts the capabilities a participant has to provide a service.

In the case of the most relevant Enterprise Architecture frameworks, as already referred, the concept of capability is present, although in some cases not directly related to that of service. Concerning TOGAF, the concept is present in the meta-model although not directly related with other concepts belonging to the business architecture or to the application architecture, particularly the concepts related with services (i.e., Business Service, Information System Service). The framework also sports a capability-based planning guideline, which consists on high-level considerations on how development and improvement of organizational capabilities should be carried. In the case of DoDAF, as shown in Figure 2, the two concepts are present in the meta-model and are related with each other: a capability is realized by a performer, which in turn might be a service. The DoDAF also includes a *Services Viewpoint*, which depicts the solutions and relates these to capabilities and operations. The case of MoDAF is similar to that of DoDAF.

In fact, the concept of service seems to rest between that of capability and those directly related to the implementation. Capabilities are easier to link to the drivers and motivation of the business, thus becoming a useful concept to business stakeholders, in the sense that it is easier to understand than more technically oriented concepts. Similarly to the way the concept of service works concerning the technical implementation of a solution, the concept of capability creates an anchor model that does not change in face of changes in the way business is implemented. In fact, this characteristic is already present in capability maturity models, since the maturity level is what is subjected to change, not the capabilities themselves. As a service allows for the consideration of different implementation options, so do capabilities in relation to services. For instance,

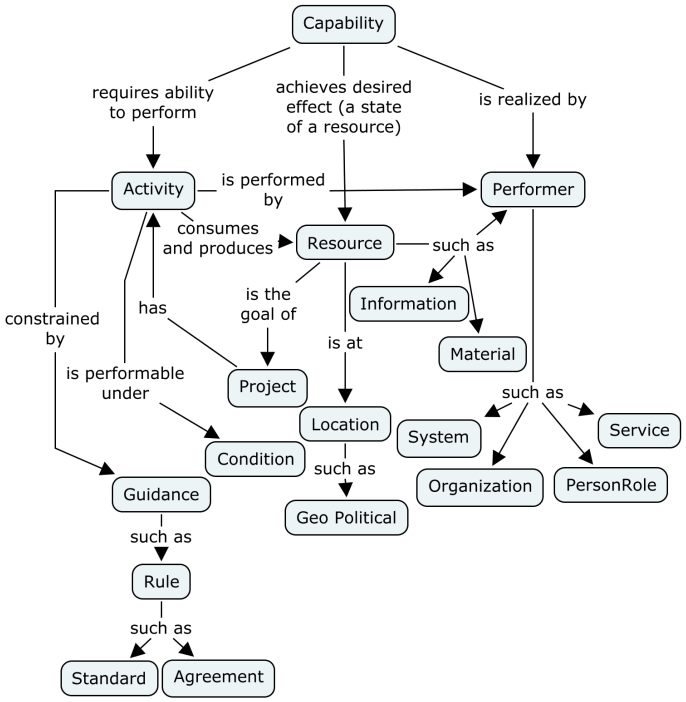

Fig. 2. Capability and associated concepts in DoDAF

considering a phone book application, the capability of providing contact information might be delivered via a browsing service or a querying service.

These facts alone are sufficient to highlight the importance of the concept of capability as one more contribution to business/IT alignment, in articulation with the concept of service. Services provide an uniform and abstract interface from the business to IT, while capabilities provide an uniform and abstract interface from strategy to business. In that sense, the full potential of an organization will only be provided if the service strategy is aligned with the business strategy. The concept of capability can promote that alignment.

Figure 3 depicts a proposal concept map displaying the relationship between the concepts of capability and service, based on the sources described throughout this work. A capability is realized through processes (which involve people), and is driven or constrained by the availability and quality of the resources, and by the strategic decisions made. A process might in turn orchestrate business services[4] or might be a part of a larger grained business service. In turn, business services provide and/or consume data entities, and if these services are fully automated, then we are referring to information systems services, which are realized by application components and implemented on technology components.

[4] In line with the definition of service provided in [14], a business service consists in the performance of activities, work, or duties associated with a product. The term is used here to distinguish between fully automatized and (semi-)manual services.

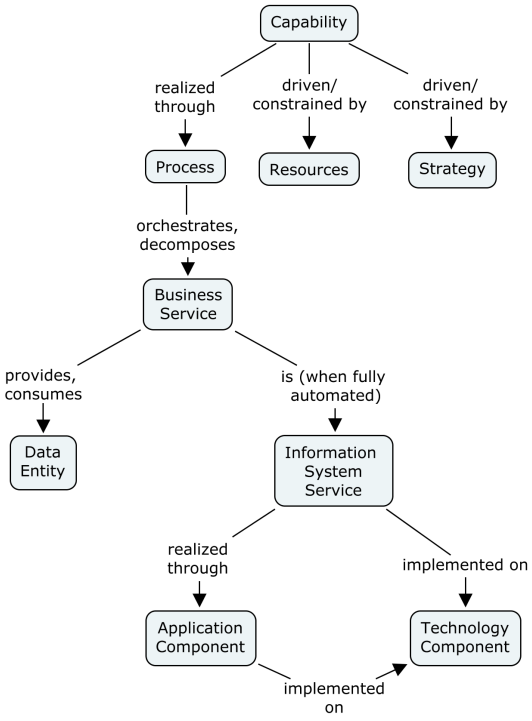

Fig. 3. Relationship between Capability and Service

7 Conclusion

This work provided an overview on usages of the concept of capability. It has been deemed useful by different knowledge communities, such as the examples of economics and strategic management, systems and software engineering, and information systems, and has been employed to describe products, systems, or even organizations.It can be described as being delivered by a determined configuration of the organization's resources and it is influenced (driven or constrained) by the surrounding environment.

The relationship existing between the concepts of capability and service is also described in this work. Capabilities seem to bear the similarities with services, namely their low coupling and high cohesion. However, the concepts are different since the concept of service seems to rest between that of capability and those directly related to the implementation. That fact can be deduced from different modeling frameworks already making use of the concepts.

In fact, the concept of capability can be used to promote business/IT alignment, in articulation with the concept of service. In fact, most of the works described make use of both concepts. However, either the direct relationships between the concepts are not present or no relationships are made with strategy concepts and/or with implementation concepts. Due to that fact, a concept map

was elaborated (Figure 3) relating relevant concepts through the use of simple relationships.

Future work will focus on the exploration of the concept in methods and techniques for service design, engineering, management and governance. In methodological terms, the existence of an approach for engineering and governing services that takes advantage of the concept of capability would better promote the alignment of service implementation with the business strategy. Associated with this, the existence of techniques for the identification and representation of the capabilities and respective association with services and organizational goals would complement this work.

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