A Flow Based Foundation for Capacity Dimensioning

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Abstract. To proactively decide on the volume of capacity available in a period of time is referred to as capacity dimensioning. The actual dimensioning of capacity concerns both the regular capacity, to cater for systematic variations, and safety capacity, to handle the stochastic variations. Despite the critical impact of these two types of variations, the support in the literature is limited in terms of formal methods for resource management based on dimensioning of capacity in general, and of safety capacity in particular. Capacity is one aspect of resources' capabilities and as a point of departure for developing such methods, the two overarching challenges of form-place-time (FPT) matching and capacity balancing are defined. These challenges are exploited to provide a holistic approach to the combination of capacity and the generic form, place and time transformations performed to create customer value. This approach requires alignment between these types of transformation to enable a homogenous perspective on different types of resources such as machines and stock shelves. Such transformations are performed over time and a discrete-time period-based approach requires that the intra-period transfers and inter-period variations are integrated. Finally, the preconditions for proactive and reactive control related to capacity required are outlined. A foundation for capacity dimensioning is then established based on capacity balancing, period transfers and flow control.

Keywords: Capacity dimensioning, safety capacity, Inventory control.

1 Introduction

Capacity is a property of resources and reflects their ability to fulfill requirements. Comparing capacity required with capacity available is at the core of resource management and in this context resources are usually associated with e.g. machines or operators (we adhere to the definitions by Apics [1] for the key terminology related to capacity). At the same time materials have traditionally been perceived as a complement to this type of capacity (machines etc.). In for example MRPII the priorities (materials) are planned and controlled in a first phase and then the resulting plans for materials are checked for feasibility in terms of capacity [2]. However, by applying a more generic perspective on resources it is possible to provide an integrative perspective on what in MRPII terminology is referred to as materials and capacity. The point of departure for this analysis is to shift focus from the actual materials in inventory to the resources holding the inventory. The resource in this case is e.g. the shelf or the tank holding the inventory and then the materials in inventory represent the amount of the resource that is required, i.e. the capacity required of the resource. Inventory therefore share several characteristics with other types of resources where the materials in inventory represent capacity required and the constraints of the entity holding inventory represent the capacity available. As a consequence, there are also some interesting analogies between the traditional control of capacity and the control of inventory that may be identified and exploited.

The methods for inventory control and capacity control have developed in parallel but also diverged over the years [3]. Inventory control in general has emphasized the financial implications and customer service whereas capacity control mainly has focused on the physical properties of manufacturing resources and their load, and contraction or expansion. Both inventory and capacity are however related to the performance of transformation and this is the focal point for this research since transformation as the foci enables a generalization of the applicability of capacity control. In relation to resource management it is of particular interest to compare capacity required to capacity available and as a consequence also how to establish capacity available, i.e. capacity dimensioning. The decision on capacity dimensioning sets the preconditions for the analysis of load in terms of capacity required in relation to the capacity available. The capacity required originates in the demand for output and correspondingly the capacity available reflects the capability of the resources to provide supply that may fulfill that demand. This supply is a concept that covers both being able to perform the appropriate transformation, and having sufficient capacity to actually perform the transformation in line with demand. From a regular perspective this comparative analysis concerns expected development but to cater for uncertain events it is important to also dimension some additional safety capacity and this is particularly challenging due to the uncertainties. The purpose of this research is therefore to identify the key aspects of resource management to provide a foundation for capacity dimensioning in general and dimensioning of safety capacity in particular. The business value of a resource is its contribution to the value adding transformation and hence a flow perspective is employed with emphasis on the transformation performed by the resources.

This research emanates from empirical observations of capacity dimensioning in practice where informal methods prevail. Based on empirical observations and a review of the literature (not included here), it is concluded that the formal tools available in the literature for capacity dimensioning are limited. The development of such tools requires that the fundamental logic of resource management and the related capacity control is known since this provide the foundation for capacity dimensioning based on three fundamental concepts of capacity balancing, period transfers and flow control.

2 Resources and matching/balancing

The significance of capacity available for resource management is highlighted by the challenges of capacity balancing where the capacity required is compared to the capacity available. The first step in outlining the key components of capacity dimensioning (which is the process to decide on the capacity available) is therefore to identify the characteristics of capacity balancing. Balancing may be analyzed from different perspectives but from a business management perspective the performed transformations are an important point of departure. A resource performing a transformation has certain capabilities related to the type of transformation it can perform and how much transformation it can perform.

The type of transformation is here assumed to be of three different types. Form transformation (F) is performed in manufacturing, through for example machining or assembly where the F characteristics are transformed. A typical example of F is machining of a metal part into a certain shape. Place transformation (P) is related to transportation and concerns when an entity is moved from one place to another. Examples of P are trains moving parts across a continent or a pipeline moving oil between an oil well and a refinery. Time transformation (T), finally, is created by enabling the separation in time of provisioning and consumption, which is the key function of inventory and here represented by warehousing. Replenishing inventory on Monday to cover for demand on Friday is an example of T, a part is produced at one point in time but can be consumed at a later point in time. The combination form-place-time (FPT) transformation reflects the type of transformation that can be performed but should not be confused the expectations from the market. FPT represents the mix capability of the resources in terms of the mix of transformation a resource can perform.

Besides having the capability to perform a specific type of transformation a resource must also be able to perform certain volume of transformations. This is here referred to as the volume capability of a resource in terms of how much transformation a resource can perform and this corresponds to the capacity available of a resource.

The mix capability and the volume capability represent two different types of resource capabilities. To make these capabilities operational it is necessary for each type (mix and volume) of capability required to be in line with the capability available. Required capability, in terms of mix and volume, is the capability that is required, to perform a specific transformation. Capability available, in terms of mix and volume, is instead a property of the resource performing the transformation.

In an operational context it is key for resource management to establish a competitive combination of the capability required and the capability available. For this, two fundamental challenges related to both mix capability and volume capability can be identified. For the mix capability the challenge is to identify the available FPT mix that can fulfil the required FPT mix and this is referred to as FPT matching. In addition, the resource must be able to perform a certain volume of transformation and this is referred to as capacity balancing. Both FPT matching and capacity balancing are positioned in **Table 1**. In short this boils down to a two-stage approach where the first step is to identify the right type of resource and the second step is to investigate if the resource has the capacity required to perform the transformation: First do the right things and then do the things right, i.e. first focus on effectiveness and then on efficiency [4]. FPT matching is the effectiveness dominated part of resource management in terms of being able to do the right things, i.e. the right type of transformation based on the mix of form; place; and time. Capacity balancing, on the other hand, is the efficiency dominated part of resource management in terms of doing things right, i.e. to have capacity available that is well balanced with the capacity required.

Table 1. Flow resources and capabilities.

	Capability required	Capability available
Mix capability (FPT)	FPT matching	
Volume capability (Capacity)	Capacity balancing	

In summary, the two key areas of resource management identified above are FPT matching focusing on identifying the right type of resources for the transformation to be performed and capacity balancing focusing on identifying how much of the transformation to be performed. FPT matching is fundamental in many aspects as it emphasizes that the type of transformation should be aligned but below it is assumed that the matching is already performed, i.e. the right type of resources is in place, and the remaining issue is to investigate the characteristics of capacity balancing.

3 Periods and transfer

Capacity balancing is based on a relation between what is required and what is available. Such a ratio can be defined for each instant of time in a continuous-time fashion but in most cases the time horizon is divided into segments, here referred to as periods. Each period is a subset of the time horizon and three distinct parts of a period can be identified: the start of the period, the intra-period time-frame and finally the end of the period. The start and the end of a period are the interfaces to preceding and succeeding periods and are where a transfer is performed between periods, see e.g. [5]. From a capacity balancing perspective both demand for capacity (capacity required) and supply of capacity (capacity available) may be transferred [6]: Transferred demand is demand that is not fulfilled in a period and instead fulfilled in a succeeding period. Transferred supply is supply that is not used to fulfil demand in a period and instead used to fulfil demand in a succeeding period.

The amount transferred to the next period may however deviate from what remains from the previous period. In some cases, the whole volume persists and is transferred but in others the remains are transient and lost and therefore not possible to transfer to the next period. Supply/demand can therefore be categorized as: Transient in the sense that remnant supply/demand is not transferred to the next period or Persistent in the sense that remnant supply/demand is transferred to the next period.

To summarize, it is possible to identify four categories of transferred supply/demand between periods, as shown in **Table 2**. The transferred supply/demand constitute the preconditions for the intra-period flow control and requirements.

Table 2. Flow periods and transfer of supply/demand.

	Transient (Lost)	Persistent (Backordered)
Demand (Capacity required)	Lost Requirements	Backordered Requirements
Supply (Capacity available)	Lost Availability	Backordered Availability

4 Control and capacity required

The concept of period is significant from a flow control perspective as the period represents an entity of time that can be used for scheduling. Each period has a time extension and a series of consecutive periods constitute the time horizon. The exact timing of an event, such as a customer order received or a machine breakdown, in relation to periods is not known before the actual event occurs even if a forecast may be available in advance. If the event is related to a future period it is possible to be proactive in relation to the event but if the event not known in advance of the present period the control can only be reactive. Flow control can therefore be divided into inter-period control based on expectations about events in future periods, i.e. *proactive control*, and intra-period control based on actual events in the "present" period, i.e. *reactive control*.

Proactive control can be based on for example forward scheduling or backwards scheduling in how different periods are managed in combination. During the proactive phase the expected capacity required is allocated to different periods providing an estimate of the requirements for regular capacity. In addition, the proactive control concerns the expected variations in the coming periods and this is covered by the safety capacity that is dimensioned based on the expected stochastic behavior.

The reactive control referred to here, concerns both capacity required and capacity available. For capacity required there can be both increasing capacity required (Addition) or decreasing capacity required (Reduction). The changes in capacity required may behave as a stochastic process, referred to as "Stochastic" in **Table 3** or subject to influence of the decision maker, referred to as "Decided" in **Table 3**. Combining these two types of behavior it is possible to identify four types of reactive flow control. In addition, a similar pattern can be identified for a proactive approach to capacity available where capacity available is provided for unexpected events in future periods which provides requirements for safety capacity. The reactive control of capacity available can compensate for some uncertainties through for example flexible workforce or quick replenishment of inventory.

The combination of decided and stochastic variations shown in **Table 3** provides a compilation of the alternatives related to reactive control but as such also represent the aspects to consider in proactive control. It is the combination of decided and stochastic variations that should be considered in dimensioning both regular capacity and safety capacity.

Table 3. Flow characteristics in terms of decided and stochastic variations.

	Decided Reduction	Stochastic Reduction
Decided Addition	1. Decided-Decided	2. Decided-Stochastic
Stochastic Addition	3. Stochastic-Decided	4. Stochastic-Stochastic

5 Control and dimensioning of capacity available

Capacity balancing concerns the relation between capacity required and capacity available in time-periods. The capacity available in a period is modelled as an interval ranging from the minimum capacity available to the maximum capacity available. The maximum capacity available can be assumed to be infinite if the limit is ignored or finite if the limit is considered. In **Fig. 1** the finite level is represented by “Maximum capacity available (MaAC)” of a resource. At the other end of the spectrum is the “Minimum capacity available (MiCA)” and in most cases, this is zero. However, a more general definition would be to set MiCA to a fraction of MaCA such that MiCA = $\gamma \cdot$MaCA where $0 \leq \gamma \leq 1$. MiCA then represents the minimum amount of the capacity available that must be used. For instance, an inventory resource may not be allowed to be empty but rather have a minimum level that must be used such as for some liquids where a completely empty tank is not allowed. Both MiCA and MaCA are depicted in **Fig. 1**. Capacity available is one side of balancing and represent the boundary for capacity required that can be balanced. In general, all levels of capacity required between MiCA and MaCA can be catered for in the period. Challenges arise when the capacity required is less than MiCA or larger than MaCA, i.e. when the capacity required is outside the approved interval. In both cases a balance cannot be established.

The capacity balancing challenge depicted in **Fig. 1** illustrates both proactive control and reactive control. For the purpose of proactive control, the future capacity required must be estimated to enable the dimensioning of capacity available in advance. Note that when proactive control is applied it is not known with certainty how the capacity required will develop during the future period concerned and since this development is difficult to estimate for each instant of time the focus is usually on estimating the aggregate capacity required for the whole of that period. The estimation is two-fold and for the regular capacity required, the expected capacity required is estimated as the most probable outcome for the period in total. In case of uncertainties the proactive control estimates how much additional safety capacity is required. In particular the investigation concerns the uncertainty of capacity required in relation to the limits MiCA and MaCA. In this context the capacity required is uncertain and can be modelled based on a probability distribution, such as the normal distribution. The scenarios with uncertain requirements are represented by the probability distribution for a complete period, could be valid for multiple periods, as illustrated in **Fig. 1**. The lower blue distribution on the right side represents the risk of capacity required under-shooting MiCA (scenario 2 in **Table 3**) and the upper orange distribution on the right side represents the risk for capacity required over-shooting MaCA (scenario 3 in **Table 3**). The middle grey distribution on the right side represents a situation where under-shoot and over-shot are equally likely (scenario 1 in **Table 3**). The discussion so far has centered on the capacity required but as an extension it is also possible to include uncertainty in capacity available. This aspect is however not included here due to the limited space available.

The over-shoot (capacity required is greater than MaCA) is possible for all types of FPT-transformation and related to when the capacity available is insufficient such as when machine time is lacking (F-type) or means for transportation are insufficient (P-type). In e.g. process industry it could also reflect challenges related to limited storage capacity in tanks (T-type). The under-shoot is normally less of a problem as such but it represents that the capacity required is less than MiCA. For F and P transformation this basically concerns that the capacity is not used. For T transformation there is a more extensive interpretation since when all capacity is available it also reflects that the resource is empty, i.e. there is no materials in inventory. In terms of inventory this could also indicate the presence of backorders or lost sale. This symmetrical property of overshoot and under-shoot enables the application of tools and methods for one issue to be applied on the other. For example, methods for dimensioning of safety inventory (where inventory is capacity required of the resource holding the inventory) may also be applied for dimensioning of safety capacity [6] in for example a manufacturing resource and as outlined above, the capacity may be related to manufacturing, transportation as well as warehousing (inventory). Finally, it is important to acknowledge the possible transfer of supply and/or demand between periods and in **Fig. 1** it is assumed that either all capacity is available at the beginning of the period (Scenario 3), where the orange line represent the capacity required, or no capacity is available at the beginning (Scenario 2), where the blue line represents the capacity required. Both these scenarios mean that the state at the beginning of the period is independent of the state at the end of the previous period and hence no transfer of supply can take place between periods. Consider for example the blue line that ends at the lower part close to MiCA. When the next period begins it is assumed to be restored to the MaCA corresponding to the blue line on the left.

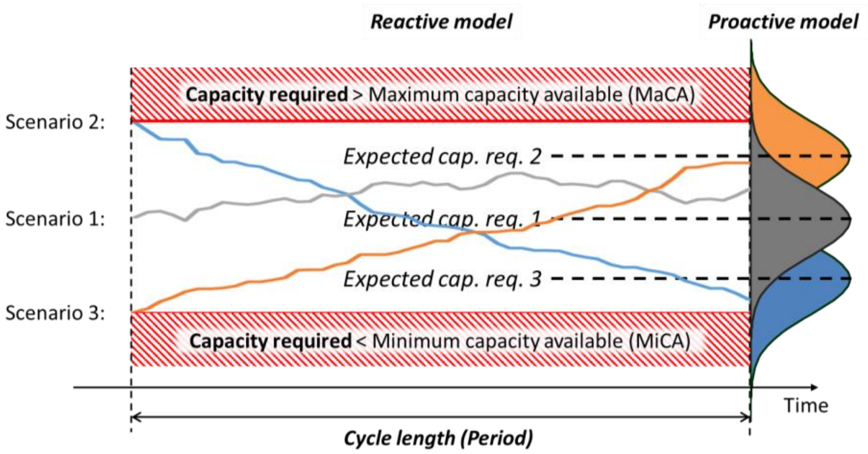

Fig. 1. Balancing, periods and control.

6 Conclusions

Capacity dimensioning concerns decisions of capacity available in future periods and this is an important challenge for managers in relation to manufacturing, transportation and warehousing since capacity available not only drives cost but is also important for responsiveness. To strike a competitive balance between cost efficiency and responsiveness requires a balance between capacity required and capacity available. The balance is traditionally focusing on manufacturing resources but the balance analysis is valid for not only F transformation but also P and T transformation. T is in particular conceptually interesting since availability is usually associated with the materials in inventory whereas this approach considers the inventory-holding entity as the resource and instead positions materials as representing capacity required. The capacity required is the result of transformations to perform, a combination of preconditions and decisions, whereas the capacity available is a management decision related to capacity dimensioning. Continuous-time dimensioning is rarely viable due to the sheer amount of decisions it implies and instead a discrete-time approach is usually employed where the time horizon is divided into periods. Proactive control enables capacity balancing in that dimensioning of capacity available sets the constraints of the flow in terms of capacity available per period. As events unfold over time the capacity is consumed and within each period a reactive control approach can be used. In summary, the three components balancing, periods and control have been integrated to provide a foundation for capacity dimensioning with a generic approach embracing all three types of FPT transformation in a similar fashion and in particular provide a foundation for dimensioning of safety capacity. Dimensioning sets the stage for each period of the planning horizon with proactive control. Note, however, that also the reactive control applied in each period must be considered in dimensioning as it may influence the capacity required as well as the capacity available in each period but the implications of these aspects require further research. In addition, this integrative approach to resource management, involving the three types of transformation, also merits empirical validation.

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