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Inventory Management: Modeling Real-life Supply Chains and Empirical Validity

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ABSTRACT

It is our intention to write a different overview of inventory models, from single item single echelon models to multi-item multi-echelon models, then is mostly provided in text books on Operations Management. We hope that this monograph provides complementary knowledge. Instead of starting with inventory models that are tractable from a mathematical point of view, we start from the inventory management problem and the modeling challenges to be faced. We present the economic order quantity problem from the perspective of Return On Investment instead of from a cost perspective. We show that the Newsvendor fractile emerges from virtually any model with linear holding and penalty costs. And we discuss the complexities of multi-item multi-echelon inventory systems by developing necessary and sufficient conditions operational control policies for such systems should satisfy.

Inventory management has been a core topic of Operations Research since the 1950s. Inventory can be seen as a means to create efficiency in production and distribution: it enables scale by allowing to accumulate demand until a batch quantity is released that can be produced and shipped efficiently. This role of inventory is of great importance in process industries, where set-up times are considerable. Inventory can be seen as a means to ensure sufficient customer service: as demand is unpredictable we must hold inventory in case there are unexpected surges in demand. This role of inventory is of great importance in retail, as we expect a product to be available off-the-shelf or at our doorstep within 24 hours.

Inventory can also be seen as a symptom of bad management, as waste of capital. Reduction of inventory capital has been high on the priority lists of CEOs over the last four decades. In the early 1980s, the Just In Time (JIT) philosophy proclaimed zero inventory as the key objective to ensure continuous improvement of processes, leading to less process variability, shorter processing time, smaller production and transportation batches, and higher product yield. In many businesses inventory is an unfavorable term. Euphemisms for inventory were introduced, such as buffers and supermarkets. Despite
the continuous efforts to reduce process durations and volatility, zero inventory will remain a mirage as fundamental uncertainty in demand and supply cannot be eliminated and trading-off efficiency, quality, customer service and cost of inventory capital inevitably yield the need for inventory at various places in global and local supply chains, acting as the lubricant.

The trade-offs to be made have been studied extensively in the inventory management literature. This has led to optimal inventory control policies for various supply chain structures with various cost assumptions. Clearly, most results are known for the simplest inventory management situation, i.e., a single product at a single location. But both the qualitative and quantitative understanding of this simple inventory management situation is a building block for understanding inventory management in practice, where we have to deal with multiple items in multiple locations.

Thus, inventory control policies are implemented in every ERP (Enterprise Resource Planning) system, such as SAP and Oracle, and used in almost every company. ERP systems are the transaction backbone systems of enterprises in which product and process data are stored and each customer order, production order, and purchase order is tracked and traced. Over the course of a few decades, ERP systems have been enriched with planning and control modules that support inventory management, production management, and sales. Despite the availability and use of inventory control policies in ERP systems, we observe that most of the control-policy-based replenishment proposals are over-written by manual decisions. Indeed, being an inventory manager or planner, you want to manage and plan, and you can do better than the inventory management system. Unfortunately, it is shown again and again that proper use of inventory management systems yields higher service and lower costs at the same time. We observe that inventory managers have difficulties with the interpretation of unexpected events regarding demand and supply, i.e., distinguishing noise from signal. At the same time we observe that inventory managers have access to relevant information that an ERP system’s inventory control module cannot exploit. This calls for the design of an inventory management approach that combines the strength of mathematically rigorously deter-
mined inventory control policies and tacit knowledge of human decision makers. This monograph is motivated by these observations and builds on 32 years of working in (8 years) and in cooperation with (the next 24 years) industry, applying and implementing inventory control models.

It is our intention to write a different overview of inventory models, from single-item single-echelon (SISE) models to multi-item multi-echelon models (MIME), than what is mostly provided in text books on Operations Management (e.g. Nahmias and Olsen (2015) and Silver et al. (2016)). We hope that this monograph provides complementary knowledge. Instead of starting with inventory models that are tractable from a mathematical point of view, we start from the inventory management problem and the modeling challenges to be faced.

The first section of this monograph is devoted to modeling inventory systems so that these models are empirically valid by proper calibration. Inventory models are abstractions that cannot capture all possible actions to balance supply and demand but with proper measurement of inventory management performance, we can set the parameters in such a way that the customer service is consistently at the right level. We hypothesize that it is better to use mathematically tractable models and appropriately chosen performance measures than to identify all possible actions under specific circumstances and model these explicitly. We found that many specific actions are focussed on preventing stockouts. Typically, such actions either postpone customer demand or expedite production orders released earlier. Herewith we create correlation between occurrences of high demands and arrivals of production orders that satisfy them. Ignoring this correlation yields considerable underestimates of customer service, while modeling this correlation is mostly mathematically intractable. Thus we propose to measure performance before specific actions are taken, which yields the notion of Intervention Independent Performance (IIP) indicators. A company must also measure the effectiveness of the specific actions taken, which yields the notion of Intervention Dependent Performance (IDP) actions. Applying IIP indicators in combination with inventory models in research projects provided an empirical basis for the validity of this approach: in both single-item single-echelon (SISE) situations and multi-item multi-echelon (MIME) inventory systems we could explain the quantitative
relationship between capital invested in item inventories and end-item customer service. One should not underestimate the importance of this finding: it provides a scientific basis for the use of inventory models as studied in OR literature. Here we take the position that mathematical models and their analysis are not science without empirical data supporting the causalities embodied by the model.

The second section discusses SISE models. We show that under linear holding and penalty costs, the Newsvendor equation holds for virtually any sensible control policy. The Newsvendor equation states that the non-stockout probability at an arbitrary point in time equals the quotient of penalty cost rate and the sum of holding cost rate and penalty cost rate. We show that inventory management performance is primarily determined by average inventory and order frequency. In our view, in inventory management education, there should be more emphasis on average inventory levels instead of safety stocks. After all, we pay for the capital tied up in average inventories, not in safety stocks. As capital is tied up in inventory, it is relevant to consider trade-offs from a Return On Investment (ROI) point of view. We discuss the impact of the change from cost minimization to ROI maximization using the Economic Order Quantity model. We discuss the prerequisites for empirical validity of the basic inventory models. One lesson should stand out here: mathematical analysis must be rigorous. Otherwise it is likely that the resulting control policies do not make any sense to inventory planners, and they are right in that case.

The third section extensively discusses MIME inventory systems. This discussion is not aiming at a complete overview of the state-of-the-art on multi-echelon inventory system research. Having worked on the subject for over 25 years, we conclude that the emphasis in the scientific literature has primarily been on optimal policies under specific assumptions on the structure of multi-item multi-echelon systems, such as serial, divergent, or convergent, (cf. Axsäter (2003) and Song and Zipkin (2003)), and much less on the underlying complexity of general MIME systems. There are no serial systems in practice. At best they are divergent (i.e., each item has a single upstream predecessor, or child) in the form of retail and spare parts distribution networks. Convergent MIME systems, i.e., systems in which each item has at most
one parent, are rare, as most companies sell more than one product. In literature, convergent MIME systems are also referred to as (pure) assembly systems. So most of the time supply chains are networks with both embedded divergence and convergence (i.e., an item may have multiple children upstream and multiple parents downstream). Under uncertainty you are continually confronted with the dilemma to allocate item availability among parent items, i.e., the items that use the item under consideration. Allocating less to a particular parent item implies that less is needed of other child items used by this parent item, whereby these child items can be used for other parent items, but then we need other items as well. We assume that orders released to the shopfloor can be executed with 100% due date reliability, provided that material (and resource) constraints are taken into account. This implies that we model general MIME systems with constant flow times, i.e., constant times between order release and order receipt in inventory. In order to create a benchmark for control policies for general MIME systems, we formulate necessary conditions for a control policy to yield feasible solutions. Herewith we bridge the gap between mathematical programming formulations of supply chain planning problems that concern the problem to be solved today, and the stochastic dynamic programming formulations that focus on control policy structures that generate optimal policies, and resulting solutions, over a relevant period of time.

The most frequently used planning logic to plan and manage MIME inventory systems in practice is called Material Requirements Planning (MRP I). The main principles of MRP I logic are lead-time offsetting and dependent demand. Starting from the constraint to maintain a safety stock at the end of each future period, and knowing future (gross) requirements for an item, as well as outstanding orders, inventory balance equations are used to determine the replenishment quantities in future periods. By offsetting the replenishment quantities by the item lead time we obtain planned order quantities. These planned order quantities are translated to so-called dependent demand for child items by multiplying the order quantities by the number of child items needed to make one item. Through proper administration we can determine the dependent demand for each item and derive the planned order for each item. For further details on the logic we refer to subsection 4.4. Initially
Material Requirements Planning was abbreviated as MRP, but in the 1980s the MRP logic was embedded in an overall framework for planning and control called Manufacturing Resource Planning, which, having the same three-letter-abbreviation, was denoted as MRP II (cf. Vollmann et al. (2005)). MRP I was introduced as a “killer app” for IBM mainframes in the early 1960s, and promoted by the American Production and Inventory Control Society (APICS) from 1970 onwards. For a historic perspective on MRP I, we refer to Wilson (2016). We find that MRP I logic does not pass the test of adhering to material availability constraints. This finding cannot be emphasized often enough, as it explains symptoms like nervousness and expediting. On my return to academia in the early 1990s, I set myself the research objective to determine safety stocks in MRP I. Pursuing this objective, I found that my quest would be in vain, because the MRP I logic is not mathematically sound. MRP I logic turned out to be a logic that generates requirements, but it is not a logic for planning. Planning involves the balancing of demand and supply, knowing that you must take decisions on supply before demand is known. That is why in general MIME systems there is a continual misalignment between demand and supply that is resolved by keeping inventory. However, inventory does not always resolve the misalignment, and that is where scarce child item material availability must be allocated among multiple parent items with the consequences sketched above: a problem mess, a Gordian knot. The concept of Synchronized Base Stock (SBS) policies for operational control of general MIME inventory systems is cutting this Gordian knot at the expense of suboptimality (though SBS policies are optimal for divergent systems and convergent systems). The SBS concept generates a deep insight into the natural decision hierarchy embedded in any general multi-item multi-echelon system. In-depth case studies in the context of MSc thesis projects at companies indicate that the assumption of SBS policies yields empirically valid results, even though none of these companies used SBS policies. The only explanation for this result is that also in MIME inventory systems inventory performance is driven by average inventories and order frequencies.

The fourth section briefly discusses the additional issues that come with taking into account resource constraints. While for single-echelon
systems finite capacity is (relatively) easy to deal with, this is not the case for multi-echelon systems. I consider the results for serial systems in Janakiraman and Muckstadt (2009) as a milestone in the analysis of capacitated MIME systems, and at the same time as a clear indication of the challenges ahead of us when trying to tackle this problem for general structures.

Inventory management is a challenging research subject due to its structural complexity, represented by general networks of interacting stockpoints, and the complexity induced by demand and supply uncertainty. The curses of dimensionality prohibit the calculation of optimal policies. I hope that this fact is a reason to pursue more research with great practical relevance. Admittedly, when allowing yourself to write down that something on the left hand side of an “equation” is approximately equal to something on the right hand side, you may be overwhelmed by the possible alternative routes that can be taken towards policies and algorithms. Yet at the end of the day, applied science should be about reality and reality happens to be complex.
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