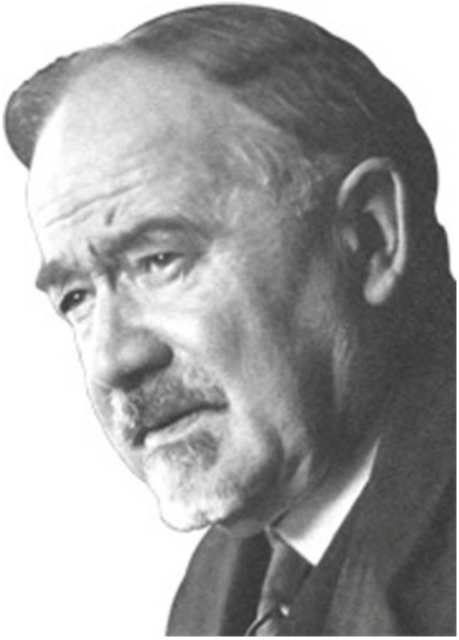
Alfred Weber (1868–1958): The Father of Industrial Location Theory and Supply-Chain Design

Richard L. Church



Alfred Weber. *Photo source* Heidelberg University

R. L. Church (✉)
Department of Geography, University of California, Santa Barbara, 1632 Ellison Hall, Santa Barbara, CA 93106-4060, USA
e-mail: rick.church@ucsb.edu

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1 Introduction

In 1909, Weber published his classic book, *Über den standort der Industrien*, a book that describes many first principles of economic production and location (Weber 1909). This book is his only major work in the field of economic geography. Most textbooks in location science, economic geography, and regional science describe his theory as a simple triangular construct of three points in geographical space, two that represent needed localized raw materials and one that represents a market. The central problem is that of locating the most efficient point of production of a good, using the raw materials that are transported to the factory, and shipping the product to the market. Weber suggests that all else held constant, the optimal location of the factory would be the location at which the sum of the three transport costs is a minimum.

This problem representation was also described in earlier work by Launhardt (1872). A geometrically derived solution to this problem is often attributed to Georg Pick, which is given in an appendix of Weber's book, even though Launhardt and others (e.g., Simpson 1750) had developed methods for determining the optimal solution many years and even centuries before Weber. Because of more recent recognition of Launhardt and, perhaps, a more appropriate attribution to some of these earlier developments, the importance of Weber's construct seems to have diminished, and many have stated that Weber has been given undue prominence for his classic work.

The goal of this chapter is to set the record straight. Simply put, Weber was, and should be considered, henceforth, an early giant in the field of regional science, primarily due to the more nuanced constructs that are described in his seminal book, but which have, for the most part, been overlooked. It will be shown that his location theory was extensive, reaching far beyond a simple "triangular figure," and relevant to many of the problems faced by industries today, including the design of supply chains.

This chapter is organized as follows. Section 2 provides a short biography of Alfred Weber. Section 3 presents the emerging consensus of Weber's contributions with respect to location theory. Section 4 discusses, in detail, the locational triangle with its relationship to the emerging location literature. Section 5 returns the focus to specific elements of Weber's paradigm that have been overlooked and are even more relevant today to regional scientists, industrial engineers, and economic geographers. Section 6 presents a final appraisal, along with a summary of some of the impacts of Weber's work.

2 Short Biography

Alfred Weber was born in 1868 in Prussia. His father, Max Weber, Sr., was quite educated and held a doctorate of law. Max, Sr., served in a number of positions that included governmental posts and leadership in political groups. Among these was a stint as a city magistrate in Berlin. He also served as a leader in the National Liberal Party. During much of Alfred's formative years, his father served in the Prussian House of Representatives and was a member of the German Empire Reichstag. Many notable scholars and politicians were regular visitors at Alfred's family home due to the prominence of his father. This certainly was a fertile environment for a young budding scholar in the late 1800s. Alfred was one of eight children, although two died at an early age. His older brother, Maximillian (Max), also became a notable scholar.

To understand Alfred fully, one also has to understand Max. Max started his studies at the University of Heidelberg and eventually moved to the University of Berlin. He worked as a junior lawyer, passed an examination to practice law, and, as well, earned a doctorate of laws. This was followed by the completion of a *habilitationsschrift* on Roman agrarian history and its significance to the law. Shortly after, Max joined the faculty of the University of Berlin. Max is considered to be one of the founders of modern sociology. His early writings had a profound effect on this field, and they no doubt had a significant influence on Alfred. Alfred followed Max into an academic career as well. He started his university studies at the University of Berlin, where Max had finished his studies, completed a doctorate in 1895, and, in 1899, started teaching there, just as his brother Max had. Alfred left Berlin in 1904 for a short stint at the University of Prague. In 1907, he joined the faculty at the University of Heidelberg, just as Max had done in 1896. Alfred remained at Heidelberg for the rest of his academic career. Two years after he joined the University of Heidelberg, he published his classic book on the *Theory of the Location of Industries.* Although he retired in 1933, he remained active in his writings until he died, at the age of 90, in 1958.

Alfred Weber is known both as an economist and a sociologist. His main contribution to economics is *Theory of the Location of Industries*, which was published in German in 1909. Carl Friedrich translated Weber's book into English in 1929, which was published by the University of Chicago. It is this English version of Weber's work that brought his work to prominence. But Alfred was highly influenced by his brother's work in sociology, as well as by his father's political perspective. Alfred is best known in the field of sociology for his work *Kulturgeschichte als Kultursoziologie*, published in 1935, which explores the relationship between knowledge and culture. From the 1920s on, Weber was so enmeshed in the studies of history, philosophy, and culture that his early work in economics appears to be but a footnote in his academic career. However, his book on the theory of industrial location was an early view on industrial development and clearly influenced regional scientists and economists, including Palander (1935), Hoover (1937), Isard (1949), and Moses (1958). It is interesting to note that scholars either know about Alfred Weber for his location book or for his works on culture and history, but not for both. From what I know from discussions I had with Walter Isard, I suspect he was quite aware of Alfred's accomplishments in cultural sociology. But Isard was definitely influenced by Weber's industrial location book and covered elements of this work in his book, *Location and Space-Economy,* as well as in many papers.

3 An Emerging Perspective on Weber's Work on Industrial Location

It seems that every regional scientist knows something about Alfred Weber and his industrial location model that involves the optimal location of a factory that produces a product, requires two localized raw materials, and serves one market center, where the objective is to minimize the costs of transportation of the raw materials and the finished product. If you hold demand, prices, and labor costs to be constants, then it is an easy task to design a production plant to efficiently produce enough product to meet demand. Weber divides raw materials into two classes: ubiquitous and localized. If all materials are ubiquitous, then it would make sense to locate the factory at the place of consumption or market. But, if some of the raw materials are localized, then they must be transported to the place of production. What is left is to locate the facility in such a manner that the sum of all transportation costs is minimized.

The problem is typically depicted as a location triangle, as given in Fig. 1a. All diagrams in this chapter that represent some form of a Weber problem involve triangles to represent localized raw material sources, circles to represent demand/markets, and squares to represent the factory location. The fact that this locational triangle is

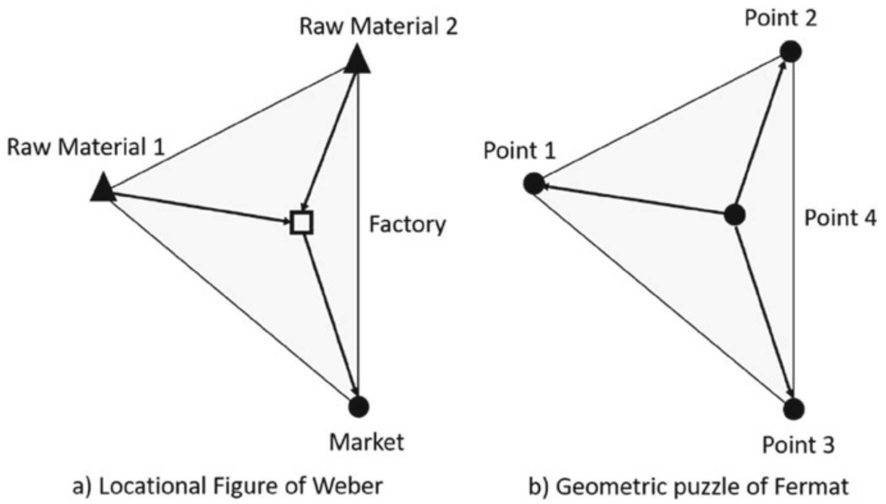

Fig. 1 Depiction of the classical locational figure of Weber showing its similarity to the triangular problem of Fermat to find the interior point minimizing the sum of the distance to the vertices. Weber's figure is usually called the "locational triangle," but Weber viewed this as a simple form of a more complex diagram, simple enough to convey that the industrial activity will be placed somewhere within the region of points defining the geography of the problem. Here, in Weber's figure and in subsequent diagrams, circles represent points of demand, triangles represent raw material locations, and squares represent factory location(s). *Source* Drawn by the author

a universally understood view among geographers, economists, and regional scientists is due to widescale coverage of this model in introductory courses in economic geography, location science, industrial engineering, and production and operations management.

Weber in his classic book also made several important observations about production orientation and agglomeration. Depending upon the product being made and the relative amounts of raw materials being used, Weber described the pull in locating a plant toward a resource or close to a market: toward a resource when most of the weight of the resource is being consumed in the production of the product and close to the market when the weights of ubiquitous materials make up a considerable portion of the final product. In fact, Weber goes into great detail about the role of relative weights of materials in factory location. He also suggested that certain elements of the landscape fabric would evolve with the introduction of an industry. This includes the rise of a specialized labor force, and even infrastructure that would support certain types of industries. Such an emerging infrastructure may include specialized educational programs, transportation elements like rail sidings, and supporting industries (making the screws and other products that may be needed in an assembled product of some other firm). Weber stated that these evolving elements supported an agglomeration of associated functions. That said, is this the total sum of Weber's book? Do we need to look any further than what we have read in introductory texts on Weber, or did Weber actually create a much richer theory of industrial location? That is, have most of us overlooked something in his book or maybe never read it? Besides, today, many have changed their focus to understanding the factors and policies which give rise to an industry in a region rather than the process of location selection.

Before digging deeper into Weber's classic, I would be completely remiss if I did not recognize the discussions of Weber by Pinto (1977) and Perreur (1998). Pinto (1977) was the first to raise questions concerning the importance of Weber when he stated that the industrial location triangle was actually proposed by Launhardt in the 1870s, nearly forty years before Weber's book. In fact, Launhardt's construct was more nuanced than Weber's, as Launhardt was interested in the construction of the underlying transport infrastructure as well. This lack of long overdue attribution is due to the fact that Launhardt's work was never translated from German and, for the most part, remained in relatively obscure manuscripts. Perreur (1998) also discussed Weber in light of Launhardt and even asked the question: "Should we forget about Weber?" To be accurate here, it should be noted that Perreur answered this question by stating that Weber's discussion of specialized labor and agglomeration tendencies were, in fact, groundbreaking critical observations, but, like Pinto, he credited the location triangle to Launhardt (1872). Others (e.g., Laporte et al. 2015) have since followed this line of criticism and have begun to give principal credit to Launhardt and not to Weber.

Another undercurrent in the discussion of the location triangle is that the "triangle problem" arose in the mathematical literature several hundred years earlier (see for a detailed explanation Wesolowsky 1993). It is stated that Fermat posed the following mathematical puzzle: Given three points, what is the location of a fourth point that minimizes the distances to the other three points? Note that this puzzle was a purely geometrical one and was not related to anything that was economic or practical for that matter (it is depicted in Fig. 1b). Wesolowsky was not acquainted with Launhardt, but he was with the developments of Calverli, Torricelli, Steiner, and Simpson. He concluded in his review of the Weber problem that the naming of this problem was due to the "imperialistic control of the economists." To be perfectly clear, the problem posed by Fermat was purely a puzzle, whereas the one proposed by Launhardt and Weber described a problem that deals with the efficient location of an economic activity. Furthermore, the problem proposed by Fermat was but a special case of what was described by Launhardt and Weber. This is because Launhardt and Weber required hauling various weights of materials to the factory as well as hauling the finished product to the market. Even though the costs of shipping were a function of distance, they varied depending upon the amounts needed from a given source, amounts of product supplied to the demand, the attributes of the materials and products (bulky, dense, breakable, etc.), and the transport mode. The assumption in the Fermat problem is that the distances to the three points are just distances alone, making it an unweighted sum of distances problem. Since Fermat's problem is just a special case of Launhardt's and Weber's, it is quite presumptuous of Wesolowsky to call the naming an imperialistic move on the part of economists!

Altogether, past reviews and discussion in the regional science literature (e.g., Pinto 1977; Perreur 1998) and location science literature (Laporte et al. 2015; Wesolowsky 1993) have intimated or even outright suggested that Launhardt be credited with this problem. Such conclusions reflect a lack of understanding of what Weber proposed. I hold the view that this is probably due to the fact that most if not all of the current researchers in our field have not read Weber's book but only derivative works in textbooks and review papers. Without a full understanding of Weber, beyond the aspect of agglomeration and deagglomeration, one could easily ask the same question that Perreur (1998) did: Should we forget Weber? The main goal of this chapter is to put Weber's work into perspective, describe the richness of Weber's paradigm, and demonstrate without a doubt that Weber was way beyond his time, contributed a fundamental understanding to efficient resource allocation and industrial location, and belongs among the group of luminaries such as Koopmans, Beckmann,[1] and Kantorovich (Koopmans 1951; Koopmans and Beckmann 1957; Kantorovich 1939).

4 Understanding the Details and History of the Locational Triangle

To fully understand how recent scholars have touted the work of Launhardt over Weber, it is first instructive to present Launhardt's model. The problem is basically the same as what is depicted in Fig. 1a, except there is an additional element: The

[1] For a discussion of Martin Beckmann's contributions, which place him in the pantheon of *Great Minds in Regional Science,* see Mulligan (2020).

costs of developing the transport links are also included rather than just the haulage costs. For the sake of brevity, consider that the raw material sources are numbered and indexed by i, the markets or demands are indexed by j, and let the location of the factory be defined as point (x, y). Consider the following notation:

V: the annual interest and principal cost and the yearly cost of maintenance cost per kilometer, associated with the building of a conveyance system (road or rail)
C: the transportation cost per ton per kilometer
t_i: the distance from point i to location at (x, y) where i represents a raw material location.
d_j: the distance from the location at (x, y) to point j where j represents the location of market $j = 1$
w_i^R: the volume (tons) of annual traffic needed to be hauled from source where $i = 1$ or 2.
w_j^M: the volume (tons) of annual traffic needed in supplying the market $j = 1$.

Using this notation, we can pose the following transportation investment and location problem: Find the point (x, y) which minimizes Z, where:

$$Z = \left(V + cw_1^S\right)t_1 + \left(V + cw_2^S\right)t_2 + \left(V + cw_1^M\right)d_1 \tag{1}$$

Equation (1) represents the essence of Launhardt's model. It involves locating the factory in order to minimize the sum of transport costs as well as the investment costs of the underlying infrastructure needed to convey the raw materials to the factory and the finished product to the market. Launhardt assumed that all distances were calculated as Euclidean, as did Weber and Fermat. If we let $V = 0$ (no infrastructure investment), then the model is that of Weber. If we let $V = 0$ and all of the cw terms = 1 (nothing is transported, only distances count), then we have essentially the Fermat problem. Thus, the Fermat problem is a special case of the Weber problem, and the Weber problem is a special case of the Launhardt problem. So, if this is all there is, one can easily view Launhardt's model as being superior to that of Weber. But, to hold this view, one needs to ignore most of Weber's book.

It is worth noting that Simpson (1750) proposed a weighted version of the Fermat problem and developed a method to optimally solve it. So, technically, Simpson had developed a solution method for Weber's construct of three points more than 150 years before Weber's book. I am unaware of any early literature that suggests a practical application to this problem until Launhardt (1872). Launhardt also developed a solution method for Problem (1), which has since been used in forestry (Greulich 1995) and recently described in Laporte et al. (2015) as an overlooked development. Consequently, the method developed by Pick to solve the three-point problem of Weber (given in the appendix of Weber's book) was not really necessary as it had been formally solved twice before.

Given the emerging view that Weber's construct was not new and that there already existed methods for its solution, you can perhaps understand how Weber's work has been discounted today. But before I attempt to set the record straight, let me quickly review a few key model and solution developments that followed the work of Weber. Later, it will be clear that these developments have tended to nibble at the edges of Weber's paradigm rather than tackle the key problems described by Weber.

Andres Vasonyi, working under the pseudonym of Weiszfeld, published an article in a Japanese journal that was written in French (Weiszfeld 1937). This article presented an algorithm for solving an *n*-point Weber problem. That is, he solved a weighted *n*-point problem involving Euclidean distance. Some refer to this as a minisum problem on a plane, where the term "minisum" represents minimizing the sum of weighted distances to a number of points. Although there is one issue of convergence that was neglected by Vasonyi, this article went unnoticed in the English literature until many years later. In the 1960s, Cooper (1963), Kuhn and Kuenne (1962), and Vergin and Rogers (1967) each independently developed a Weisfeld style of algorithm for the weighted *n*-point problem. Vergin and Rogers (1967) also proposed a simple procedure for solving this problem optimally when using a Manhattan or grid metric. Wersan et al. (1962) proposed a liner programming model for this same problem for Manhattan or grid distances as an approach for locating an incinerator within a city. Kuhn and Kuenne and Cooper called their problem an extension of the Weber problem, that is, a generalized Weber problem due to that fact that their problems involved more than three points.

Within the regional science literature, Isard (1956) described several location problems and used isocost contour lines (isodapanes) to describe the composite costs across a landscape for the location of a facility. He correctly attributed this approach to Weber, who first suggested the construction of isotims and isodapanes. Such cost terrains are easily calculated today using tools such as MATLAB, which did not exist a century ago. That is, Weber proposed a solution/visualization methodology that can be used to identify the optimal (lowest cost) point as well as easily find all solutions which are within a given percentage of optimality. Cooper (1964) also proposed a multi-facility form of the Euclidean minisum problem, where the objective is to find the optimal location of *p* facilities, where each of the *n* points is assigned to their closest located facility, and where the total weighted distance of all *n* assignments is minimized. Cooper (1964) considered this problem a generalization of Weber's because he addressed a multi-facility location problem and assumed that Weber did not. This research work is followed by a number of articles that improve on the basic solution algorithm, propose methods to handle cases of negative weights (Drezner and Wesolowsky 1991), address problems where distances are asymmetric (Drezner and Wesolowsky 1989), deal with the existence of linear or polygonal barriers (Katz and Cooper 1981; Klamroth 2001), as well as other elements. But these developments never really address the central problems raised by Weber, because Weber is viewed through the lens of a location triangle and not his complete paradigm.

In the next section, I describe a number of major issues that most of the research literature has pretty much ignored, and that are why, in my opinion, these developments have tended to nibble at the edges of Weber's paradigm rather than to tackle the key problems described by Weber.

5 Back to Weber: A More Complete Picture of His Paradigm

I use the term paradigm here to suggest a larger and more complete framework of location problems instead of the term location triangle, a terminology never used by Weber: He called it a "locational figure." That is, Weber has been pigeonholed with a problem consisting of three points, whereas his book describes a richer and far more complex view of factory location. This will quickly be apparent in this section.

Weber used a three-point construct to convey the spatial properties of the location problem, but he never stated that the key problem was relegated to three points. His view was that the central problem could involve a number of different raw materials that were sourced locally and possibly many markets. When Kuhn and Kuenne (1962) suggested a solution method for an *n*-point location problem, they called it the generalized Weber problem because they erroneously viewed Weber's construct as consisting of three points only. Figure 2a depicts the problem viewed by Kuhn and Kuenne as a generalized Weber problem, which is comprised of a number of points all being served by a central facility. The problem as described by Kuhn and Kuenne is to minimize the total weighted distance of serving all demand. Figure 2b depicts a slightly more complex version of the classic form of Weber's locational figure. The depiction in Fig. 2b is based on text given in the English translation of Weber (1929). Figure 2b contains a simple location problem where there are more than three localized raw materials (see Weber 1929, p. 64) and more than one market where the product may be distributed "*for all other places of consumption for which it gives better transportation costs…*" in all directions (Weber 1929, p. 71). The major distinction between Fig. 2a, b is not in the number of points, but in recognizing that there is a difference in the direction of raw materials and product flows, where raw materials are brought to the facility and products are taken to market areas. At first, one might consider this to be such a slight distinction, and that it is hardly worth mentioning. However, this distinction is a key to understanding Weber's paradigm.

When locating one facility where there is a set of fixed and limited raw material location sources (one source for each needed raw material) and one or more markets, the transportation costs are not dependent on the direction of the material and product transport. Consequently, such a simple construct can be solved by the methodology proposed by Weiszfeld (1937) or any of the later developments. This approach does not handle all of the components of the problem described by Weber when stating that the locational figure represents the closest sources of each needed raw material. This means that, as a factory position is moved across a landscape, its sources of allocated raw materials will change. Thus, the location of the factory will, in part, be determined by which given raw material source is closer or has least overall cost, as well as by which markets are to be served. When there is more than one source of a given raw material, then the optimal factory location will be controlled, in part, by raw material resource allocations.

Looking beyond a locational figure that is distilled to three points, the actual problem landscape envisioned by Weber is more like that given in Fig. 3 (see Weber

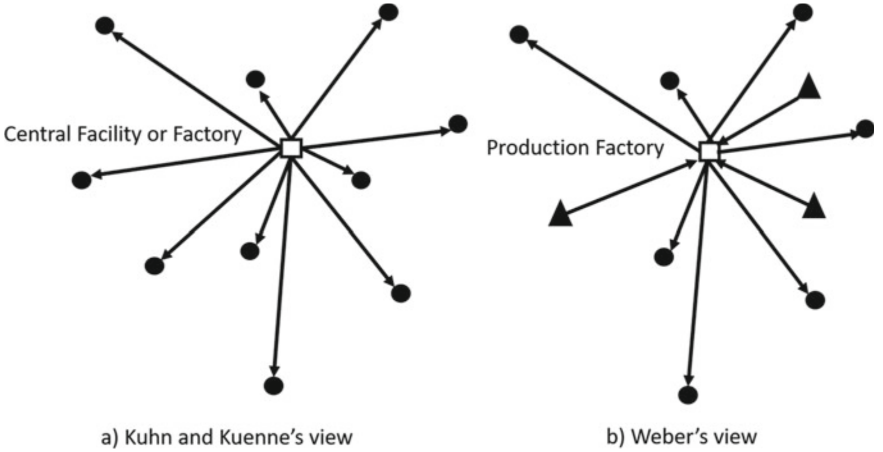

Fig. 2 Depiction of Kuhn and Kuenne's problem along with a depiction of one form of Weber' paradigm. Kuhn and Kuenne (1962) locate a facility to serve a number of demands, while Weber locates a facility that considers supply flows (from needed localized raw material sources) and product flows (to demands) simultaneously. *Source* Drawn by the author

1929, p. 68, where he describes competing locations of the same type of raw material). Figure 3 depicts several options for sourcing two different raw materials, while serving one market. (Fig. 3a depicts a possible location at position A, and Fig. 3b depicts a possible factory location at position B.) The closest sources of raw material 2 change depending upon the factory location. Weber summarized this by stating: "Naturally that deposit will be chosen whose use entails the smallest transportation

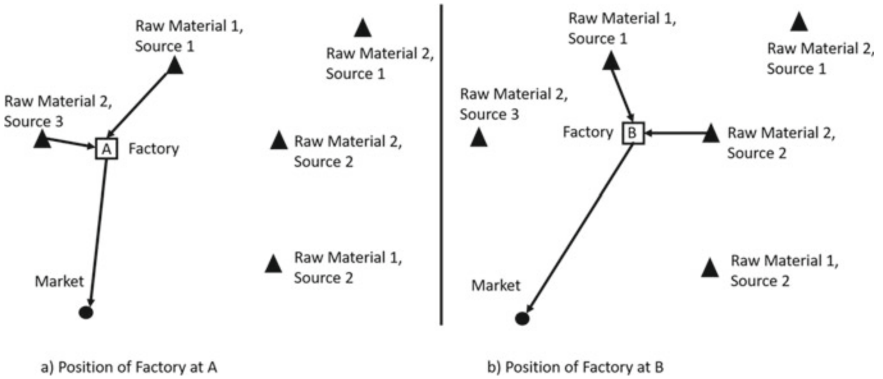

Fig. 3 Depiction of a problem described by Weber in which multiple sources of a given type of localized raw material exist. **a** Depicts the raw material allocations made when factory is positioned at location A, and **b** depicts the allocations made when the factory is positioned at location B. Thus, the mathematical formulation of this problem must contain allocation variables. *Source* Drawn by the author

costs" (Weber 1929, p. 70). He even demonstrated that the closest source of a raw material to a given market may not be the one used in the product that is shipped to that market (Weber 1929, p. 68). To model this, we need to introduce allocation variables for each of the raw materials and their sources, a fact that has been overlooked for over 100 years. A formulation of this problem, which involves alternate sources for each needed raw material along with source allocation variables, has recently appeared in Church (2019), and details for solving this problem can be found in Murray et al. (2020).

Weber stated:

> …it can and will happen that the normal output of the natural deposits of the most favorable [raw material] may not be sufficient to supply the demand of the place of consumption. In this case, less favorable … material deposits will come into play. (Weber 1929, p. 70)

Technically speaking, Weber is describing the case where several sources of a given raw material may need to be used.

Taking the same example presented in Fig. 3, Fig. 4 depicts the case where two sources of raw material 2 need to be used in order to meet the requirements for making enough product to meet the demand for the market.

If all raw material sources are large enough to satisfy all demand for each needed material at a given factory, then there is no need to go beyond the closest raw material source for a specific factory location. But, if sources do not have the capacity to fully satisfy the needs of a factory, then the issue is to purchase from multiple sources the needs while minimizing transport costs. Weber in his construct clearly assumed that the market price for a given raw material was the same at every location and was based upon taking ownership at the location of the source. To include this in a

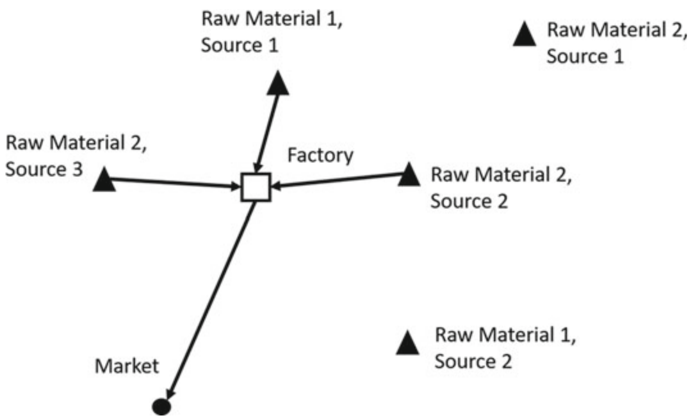

Fig. 4 Weber's envisioned case where raw material sources may have a maximum capacity to provide a given material, and additional sources of the same raw material may need to be used. Here, the factory requires raw material 2 from source 2 and source 3. The allocations and factory placement represent that point at which the sum of all weighted distances is minimized. *Source* Drawn by the author

model, one needs to introduce variables that represent the amounts of material that are acquired at each raw material source. In addition, constraints must be included to ensure that the right amount of each raw material is shipped to the factory and ensure that raw material allocations do not exceed the capacity of any source (see Church 2019).

One of the issues that I believe is misunderstood is the definition of what a raw material represents. Although many texts describe the locational figure using primary materials like iron ore and coal, Weber's view of needed materials included products from other factories. That is, most texts suggest that the factory produced a product from primary materials, whereas Weber clearly states that this is not necessarily the case. For example, if a company makes a product that requires sheet metal, screws, and paint, then either the company considers these components to be raw materials, or it makes these materials as well from primary sourced materials. Weber stated that some of these needed materials might be produced by the same firm in a system of supply that may easily involve multiple locations. He described this in the following excerpt:

> Let us suppose that an industry is influenced only by the cost of transportation, and let us neglect all of the deviating influence of labor and agglomeration. What, given such assumptions, does it mean that the production process does need to be entirely performed at one location, but split into a number of parts which may be completed at different locations? The only cause which could lead to a resultant transfer of the parts to different locations would obviously be that some ton-miles would be saved in the process… (Weber 1929, p. 174)

What Weber described is a somewhat complex industrial system, where some components may be produced at a given location and then be shipped to a second factory where other items may be fabricated and assembled, including the items produced at the first factory (see Fig. 5 as an example). That is, such systems involved staged production, where several stages of production are to be located. Suggesting such a problem clearly places Weber as having not only an understanding of a possible

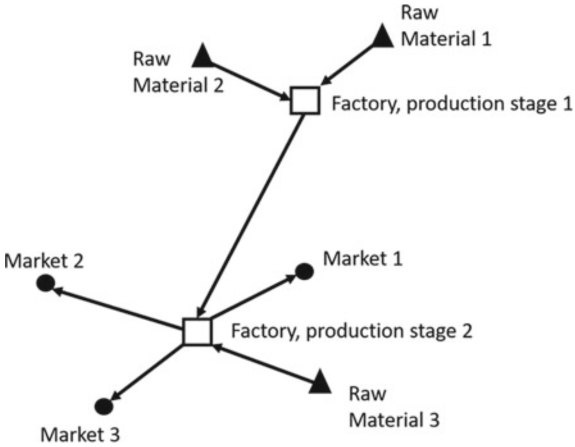

Fig. 5 Depiction of a two-stage production system, with different resources/materials needed at each stage. *Source* Drawn by the author

supply chain, but as having proposed a problem of locating a set of coordinated facilities that at the final stage results in a finished product that is shipped to market centers.

Such systems are not relegated to complex production systems, but even simple ones as well. For example, Church (2019) discusses coffee production as a staged system that fits exactly the issues raised by Weber in staged production. Coffee is usually grown on small farms, picked as coffee cherries, and is brought to local buying centers, where the crop is partially dried. The process of drying reduces the weight as well as the costs of transport to a central production facility. At the plant, the beans are extracted from the cherries and dried again. Then, the remaining beans are graded and shipped for export. The major goal in accomplishing these processes as close to the farm areas as possible is to minimize shipping costs, for the bean itself is only 20% of the weight of the cherry. The beans are then exported, and final processing, like roasting, grinding, and packaging, takes place near the final market. Thus, this is a split production system: one, which takes place near the farms, and a second, which takes place near the markets. Weber summarized his comments on split production systems by stating: "single location of production will be the exception and a split of production into several locations will be the rule for productive processes which can be technically split" (Weber 1929, p. 178).

One of the least understood elements in Weber's text is his perspective on several industrial plants that make the same product. The answer to this is a bit hidden and scattered among several sections of his book. But, this is unquestionably within the scope of Weber's original work, as he broached the issue of multiple facilities when describing that the "locational figures will always be individual or specific for a particular plant. These weight figures are general, applying to all plants of the same kind of production" (Weber 1929, p. 55). His vision appears to be that of a landscape with a number of industrial plants of the same type. Each plant would require resources for the production of the product, and each plant would serve a set of markets (see Fig. 6 for an example). For each production plant, one can draw a locational figure, which includes raw material sources supplying the plant and markets served by the plant. A simple locational figure would involve a market and one or more material sources. More complex ones would involve a host of material sources and markets. Figure 6 depicts two production plants, along with what we might call their unique resource and service sheds (analogous to watersheds). Each resource and service shed represents a locational figure and represents a locational problem.

From Weber's perspective, each factory needs to be optimally placed within its given resource and service shed, a strategy taken by Maranzana (1964) and Schultz (1969) in early examples of solving a multiple facility location problem. Clearly, Weber was interested in the placement of each factory at the optimal position within its resource and service shed, but what Weber didn't discuss was how the landscape of service regions would be defined. He also didn't state that this was the result of one company making multiple location decisions or the result of the decisions of a number of independent companies. Whatever the case, we shouldn't view this as a shortcoming, but rather a formalism that was emerging long before the techniques

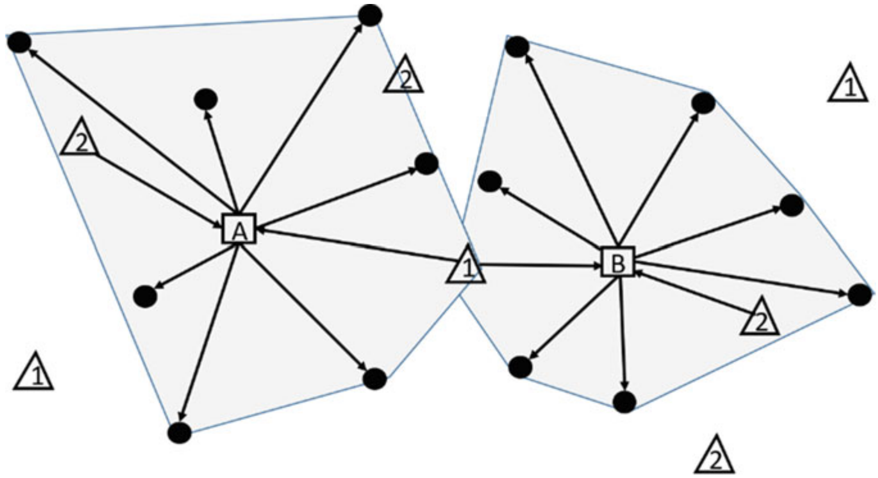

Fig. 6 Depiction of a multiple facility location problem. The numbers in the triangles signify the type of raw material available at that location. Note that all demand is served by the two facilities, and the raw material source 1 in the center of the diagram is shared by both production facilities. *Source* Drawn by the author

of optimal resource allocation and mathematical programming had been formally proposed. That is, before the Nobel Prize-winning work of Koopmans (1951) and Kantorovich (1939).

There probably is a lingering question that you might have: Does this paradigm actually fit the types of conditions that we see today? For example, China became a powerhouse in manufacturing because of its cheap labor as compared to Europe and North America. This was aided, of course, by significant government investment and lax environmental policies. It would seem that a focus entirely on transport costs would entirely miss moving production to such a distant location from the USA or Europe to take advantage of low-cost labor and reduced costs of environmental control. Before the era of containerized cargo, ships were loaded and unloaded by longshoremen. This was a time-consuming and costly process, and ships often spent more time in a port than at sea (a truly inefficient use of a transport vehicle). With the exception of bulk cargo such as grain, coal, and iron ore, transport costs at sea were high enough to hinder global trade except for products that were not manufactured everywhere. In the late 1950s, Malcolm McLean experimented with shipping loaded truck trailers between ports in the Gulf of Mexico and the east coast of the USA in order to reduce trucking costs. This was so successful that he started to experiment with using containers instead of trailers, which were easier to load on a ship and could be stacked efficiently. By the mid-1960s, a great transition was made from relying on costly hand loading of ships to using cargo containers. This led to a substantial decrease in the per mile shipping costs for ocean transport. Weber stated that different modes of transport could come into play, but his main focus in his book was to describe those industries where transport costs played a major role in deciding where a factory would be located. So, in this instance, how would China be competitive as a manufacturing location when transport costs would be increased substantially by moving a plant to China? That is, it seems that a global search for cheap labor doesn't fit into Weber's paradigm. But, just like a number of complexities, including split production, Weber raises what he calls "realities." Cheap labor is such a reality! Weber describes this issue in the following way:

> Every change of location away from the point of minimum transportation costs to a favorable labor location means, in terms of transportation, a "deviation," which lengthens the transportation routes and raises transportation costs above those prevailing under the most advantageous conditions. The changes of location can therefore take place only if the rise in cost per ton of product which it causes is compensated, or more than compensated, by savings of labor costs. (Weber 1929, p. 103)

Weber summarizes this reality issue in saying:

> …a location can be moved from a point of minimum transportation costs…. only if the savings in the cost of labor which this new place makes possible are larger than the additional costs of transportation which it involves. (Weber 1929, p. 103)

Thus, Weber's paradigm addresses this reality of today.

It is important to briefly discuss the notions of agglomeration and deagglomeration in Weber's theory. Weber raises the notion of agglomeration when discussing an evolving industry or sector of industry. As an example, a specialized labor force may emerge with the location of a factory. This could include workers that operate equipment in a factory or even those who are trained to repair the equipment. Other companies may want to take advantage of this trained labor force in locating a nearby plant. Other forces of agglomeration, like an improved transport system, a water system, streets, gasworks, etc., may also attract new unrelated industries. Industries also might locate close to other companies when those companies produce products that are required as raw materials in their products. Altogether, Weber describes a number of issues associated with agglomeration and what he terms the accumulation or distribution of industry. Weber notes that agglomeration may result in increased expenses. For example, agglomeration will increase the demand for land, which will result in a rise of land values. A rise in land values in one location will make other locations more attractive (by comparison), which will lead to a deagglomeration or the location of production at other locations. Weber states that: "all deagglomeration tendencies start from the increase in economic rent (ground rent)" (Weber 1929, p. 132). This leads to a weakening of agglomerative forces.

Finally, Weber discusses the notion of industrial strata, the links between industries, and the impacts that they have on location. Industries may be linked by their use of materials, products, and labor. For example, one industry may need the products of another industry to assemble their product. A specific case of this would be a company that may not make screws, sheet metal, and paint, but may need all these products to make bread boxes. That is, their manufacture is related to other companies' products and where those companies' production takes place. Consequently, there is a whole fabric of production that evolves, and each new entrant is, in part, controlled by previous developments on the landscape.

6 Concluding Comments

Weber was instrumental in describing a theory of industrial location that has, for the most part, been underappreciated. Although best known for his locational figure in the simple form of a triangle and his theory of agglomeration, the key elements of his locational construct have remained hidden in his text as most have relied on derivative works for discussion of his work. It is clear that Launhardt developed a location triangle before Weber, which was more complete in that it dealt with both the transport of the materials and product, but also the investment in the mode of transport. Launhardt's construct clearly represented his engineering interests in transport infrastructure investment. When removing the elements of the infrastructure investment from Launhardt's model, the three-point problem of Launhardt is equivalent to Weber's three-point locational figure. However, Weber's construct was not really a three-point figure as it could involve many points of localized raw materials and market locations. Further, Weber envisioned a landscape where specific raw materials did not exist at unique locations but were possibly quite numerous. This factor requires the notion of resource allocation, a formalism beyond that of Launhardt. Further, Weber clearly understood that production could be split into stages at a series of production facilities, each located so as to minimize total transport costs, where each facility is supplied by its nearest and least cost sources of needed raw materials. This problem element alone places Weber as one of the originators of supply-chain design. Finally, Weber's perspective was not constrained to the location of a single production plant for a given product, rather he conceived of a landscape of plants, each serving their own set of nearby markets. If such a production system is not reliant on localized raw materials, then this multi-plant location problem is equivalent to the p-median problem, that is, a model designed to minimize transport costs of weighted distances of serving all demand, where each demand or market is served by its closest facility. Without a doubt, the details in Weber's book describe a set of problems which form the basis for, e.g., the p-median problem, supply-chain design, and efficient resource allocation. Although Launhardt's theory was a breakthrough, Weber's was a complex paradigm on a higher level.

While many texts in production and operations management describe the Weber model as useful in factory location (or assign a Weber problem in homework exercises), it is usually described as locating a factory to serve a set of customers. This literature simply ignores the shipment of needed raw materials when describing the Weber model. Geography and regional science texts present only the simplest of depictions—that of the location triangle—when Weber himself described a rich and complex set of problems. Although research dealing with the Weber problem has addressed interesting facets of Weber's original work, most nibble at the underlying assumptions, rather than tackling the hard and complex problems that he posed. Such works include solving a problem on a planar surface with polygonal barriers to travel, linear barriers to travel, optimal placement of bridges across barriers, and distance metrics other than Euclidean, but they have not addressed key issues such as resources that are capacitated, staged production, and the inherent differences between raw material resources and demand.

Most today would think that the level of production is not fixed to meet a specific level of demand, but rather demand itself is a function of price, where price is dictated by production, profit margins, inventory and sales costs, land costs, and delivery costs. Therefore, the Weber paradigm is simple compared to what might be viewed as a complete production and location problem. In addition, Weber did not consider possible competition with other companies, or even the influence of product differentiation. It took nearly fifty years for many of these factors to be addressed in detail (see, for example, Isard 1956; Moses 1958; Koopmans and Beckmann 1957; Alonso 1960).

It is my opinion that Weber was constrained by what was known in the mathematical sciences of the day. Sure, the elements of calculus and classical constrained optimization were known by the time Weber wrote his book. This even included the concept of a Lagrangian function that was developed in the 1780s. But Karush–Kuhn–Tucker conditions had not yet appeared (Karush 1939; Kuhn and Tucker 1951), nor had the works of Kantorovich (1939), Koopmans (1951), and Koopmans and Beckmann (1957). These notable developments, along with the development of linear and integer programming algorithms by Dantzig beginning in the late 1940s, helped form a new field now called operations research (OR). The tools of OR have been instrumental in the formulation of many factory location and transport-flow problems that have had wide application in industrial development (see, for example, Breitman and Lucas 1987). My point is that Weber lacked the developments of OR, which could have allowed him to translate his verbal statements of problem issues into formal models.

Ackoff (1956) describes operations research as a science. He describes the process of OR in six steps: (1) describing the problem, (2) constructing a mathematical formulation of the problem, (3) deriving a solution for the model, (4) testing the model and the solution derived from it, (5) determining the conditions under which the solution may need to be modified, and (6) implementing the solution. In most OR applications, many people may be involved: some describing the essence of a problem, others formulating the appropriate mathematical model, and even others solving the model and implementing the solution. In a more recent work, I have argued that Weber had defined many different problems of industrial location and resource allocation that clearly fit within the scope of step 1 of Ackoff's description of OR (Church 2019). What Weber couldn't do was to use the tools that we have at our fingertips today to formulate and solve such problems. That is, Weber knew the essence of many problems faced by industry, described these functions, and looked closely at specific instances when land costs, labor costs, and prices were held fixed. With such a set of assumptions, he distilled the essence down to that of location based upon minimizing transportation costs (raw materials and products). He recognized that labor specialties may not be available everywhere and that other costs (e.g., land) may not be constant, but the modeling tools of the day constrained him in bringing such problems to subsequent stages, like model formulation and solution. Today, many of the problems suggested by Weber exist in network-based facility location models. However, with the notable exception of the recent work of Murray et al. (2020), most of his problem constructs have not been solved with respect to a continuous space domain.

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