MOBILIZATION FOR A PROTRACTED CONVENTIONAL WAR: A LEAN PRODUCTION ANALYSIS

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EXECUTIVE SUMMARY

This study of US mobilization capabilities argues that the Defense Department of the United States would benefit from the widespread adoption of the “lean” production philosophy, which could be adapted to increase the country’s defense industrial capacity. To reach this conclusion, the study assumes the possibility of a large-scale, intercontinental, conventional war between the United States and another major power such as (b) (5) and examines the war’s likely trajectory. In such a conflict, because the macroeconomic balance would be comparable, the fighting could be protracted, and industrial planning would be important to the outcome. Popular support for the war effort on both sides would likely be high, facilitating the conversion of civilian industry for wartime use. Through such conversion, rates of production above mere replacement rates could be achieved, which would be desirable in the context of a contest with a similarly sized economy. Based on war games conducted by the Long Term Strategy Group (LTSG) during 2011-12, such a conflict could feature conventional strikes on domestic industrial targets in both countries. Finally, observable indicators of rising tension and of (b) (5) build-up would likely provide the United States with some warning, allowing the country to prepare for the mobilization in advance of the outbreak of hostilities.

Mobilization preparations consistent with the philosophy of lean production would emphasize flexible, timely responses to orders from individual consumers – i.e., forces in the field. The lean approach stands in contrast to the classical mass production approach, involving reliance on long-term forecasts and stockpiles, that was used during World War II. In addition to analyzing how mass production was actually wasteful in that conflict, this study explains lean concepts and highlights some transition issues for the US Defense Department to consider, with particular attention to the categories of raw materials and energy supplies (including machine tools necessary for production); mobility platforms, weapons, and transportation capacity; and manpower capacity.

WORLD WAR II REVISITED

To make the case for a conversion to a lean approach to defense mobilization today, it makes sense to look back at what is commonly thought of as a success story, the US mobilization for World War II. Lean principles might have reduced the costs of the war and hastened its conclusion. The US defense mobilization for World War II wholly adopted the classical mass production processes that many American civilian industries had used starting in the days of the Model T, which was produced in high volumes with no customization and few model changes for decades. The two critical characteristics of this early Fordist philosophy were:

- Long-term forecasts of consumer demand were accurate enough to enable long-term production scheduling.

- From the perspective of the factory, there was no need to treat consumers distinctly; the system should be modeled as a monopsony.

Accordingly, in World War II, the government tended to make long-term forecasts of demand on a quarterly or even yearly basis, and to issue orders sized to these time periods to production firms. The government also centrally ordered units, exemplifying the principle of monopsony. But these assumptions were fundamentally unsuited to the wartime environment for two reasons:

- Demand for munitions was entirely dependent on enemy tactical behavior, fundamentally not amenable to forecasting.

- Moreover, forecasting the summation of enemy tactical behavior across all theaters was insufficient, since the consumers of munitions were distinct units with demands that were at best loosely correlated.

This inherently made any system rooted in monopsony difficult to sustain. At the theater level, before any campaign it was impossible to accurately predict whether the enemy would retreat, requiring large supplies of gasoline, or stand and fight, requiring large amounts of artillery ammunition. Because the industrial base was tied down by fixed schedules and too inflexible to make rapid changes, it took between three and six months at all stages of the war to process requests from the theater. Since it was necessary to engage the industrial base extremely early, then, operational planners had to produce a detailed re-supply schedule based merely on their best guess about enemy behavior.

Commanders understood that the planners' best guess was only that, and that the industrial base was incapable of responding to requests in a timely manner. As a response, they tended to build up surpluses at every level of the supply chain. These surpluses would enable response to an envelope of contingencies centered about the best guess of the planners. Had the Allied powers possessed infinite resources, they could have built up stocks to make the envelope of contingencies arbitrarily large. However, shipping and manpower resources could not permit stockpiling for running tank battles and sitting artillery fights at the same time, so the envelope was very incomplete. Consider these examples:

- At Normandy, the Allied re-supply schedule was prepared for a variety of contingencies, but it was not prepared for the operation to bog down as much as it did in the bocage, so there were shortages of artillery ammunition.

- After the Allied breakthrough, the theater situation exceeded the supported envelope in the other direction – there was insufficient gasoline support for Patton's advance.

The envelope strategy not only failed to match requirements at Normandy and in other campaigns but also proved very expensive in terms of men and materiel. Stockpiles at any point required deposition, sortation, inventorying, and protection, all manpower-intensive jobs. These service troops in turn required their own supplies and stocks of food and vehicles, which in turn required maintenance. The size of service forces spiraled; every American soldier engaged in combat arms was supported by three to four service troops. The footprint was extremely high relative to the combat impact. The envelope strategy also had negative effects on industry and shipping: Valuable machine-hours were spent producing items that were ultimately not used instead of items that could have saved lives. Supporting such a large footprint placed tremendous demands on shipbuilding, which placed further demands on industry.

While there was room to reform the distributional and logistical system, effective reforms to minimize cost would have had to have been rooted in the industrial base. Even though the classical mass production system was capable of extremely high efficiency in cases like that of the Model T, it was not flexible enough to respond in a constructive way to the sort of uncertainty posed by wartime. Due to the unresponsiveness of the industrial base, stockpiling with its pitfalls was ultimately the only effective way to ensure that operations could be mounted at all. Furthermore, unlike the case of the Model T, designs for munitions were evolving extremely rapidly as feedback was received from the combat theater. The only way the classical mass system could respond to design changes was to perform extensive rebuilding operations on items that had been completed according to an obsolete design, making the system less responsive still to timely demands.

The macroeconomic variables driving World War II meant that such costs and inefficiencies were ultimately permissible. The Americans had sufficient manpower to project the combat force needed to defeat the Axis, even with a very heavy footprint. By the time that most large campaigns were mounted, the German U-boats had been vanquished and shipping losses were lower than expected. Thus, there was a relative glut of shipping. Machine tool utilization hours remained far below their maximum in all industries. Despite the cost in blood and treasure of a prolonged war, the Allies were winning, which precluded reconsideration of the Fordist assumptions.

THE EMERGENCE AND TRIUMPH OF LEAN

In the postwar civilian market, the competitive position of the Japanese car company Toyota did not permit accepting the unnecessary costs associated with the mass production approach. A group of thinkers led by Taiichi Ohno invented a set of philosophical principles termed “lean” that were better matched to the demand environment. Ohno’s first key principle was that long-term forecasting was inherently a source of error relative to actual demand. Rather than “pushing” a long-term forecast on the true shape of consumer demand, lean production would produce only in response to by-the-moment “pull” from the consumer. This principle was applied not only to the whole process but to every individual step, so that no step would produce unless the step ahead of it made a pull order. Inventory, with its high carrying cost, was mostly replaced by responsiveness of the production base. Ohno and his disciples built up a set of methods to successfully sustain the flexibility that so-called “just-in-time” (JIT) production demanded. Along with just-in-time came a turn away from monopsony. A lean system was flexible enough to respond to orders from individual customers, so the market could be explicitly treated in its more complex true state, rather than classical mass production’s implicit treatment of the system as a monopsony.

To meet the price targets necessary to undercut Toyota’s American competition, and to meet the profit targets necessary for Toyota’s strategic plans, it was necessary to systemically reduce costs. Lean production developed a categorization scheme of production and distribution activities. Activities are split between those that add value from the perspective of the customer and those that represent wasted activities. Ohno and his disciples evolved methods to eliminate each category of waste. One implementation measure deserves explicit mention: Sustaining a flexible and responsive system required lean philosophers to rethink the proper role of the worker. Contrary to the trend in contemporary mass production of seeing manpower as a short-term necessity in the march toward a fully-automated factory, lean production saw the worker as bringing to the table unique capabilities that machines could not hope to replicate. Workers could make improvements to the process, offer suggestions, and make decisions. To train flexible workers, the quick training cycles of classical mass production were replaced by longer learning cycles.

By application of lean principles and methods, it is generally possible to increase labor productivity by a factor of four, decrease delivered defects by a factor of four, decrease in-system inventories by a factor of twenty, and decrease production throughput time by a factor of twenty. In industries from production of wire protectors to production of jet engines, these results have been consistently achieved.

LEAN AND FUTURE WAR

The central contention of this study is that lean philosophical principles are better matched to the requirements of military mobilization than are classical mass production principles. In particular, a military mobilization environment will necessarily involve lack of certainty in forecasting, and a monopsony is an unacceptably crude approximation for the actual wartime system, where combat units and not the buying authority are the ultimate consumers. To look beyond broadest strokes, this study stipulates a prolonged, conventional, large-scale war between the United States and (b) in 2030-2040. As on a macroeconomic level both powers are relatively evenly matched, such a conflict would necessitate efficiency in production, and would generate sufficient political will for the massive dislocations associated with full-scale industrial mobilization. With both sides launching long-range precision strikes against each other's industrial facilities, a mass production system ill-tailored to demand would be a recipe for defeat.

Clearly, there are differences between the civilian peacetime environment and the military wartime environment, but none of these differences changes the fundamental calculus, that lean production better matches the requirements of military mobilization than does classical mass production. The first crucial difference is that the military wartime environment, unlike the civilian environment, is zero-sum: All of the resources given to a project are directly denied to another project, and may cost lives. A person building airplanes is one less person building ships. This puts an additional premium on the efficiency improvements that lean production can deliver. At the same time, if there were infinite resources, it would be possible to implement a system where combat units could "pull" directly from the industrial base, replacing the idea of monopsony. However, there are resource constraints. In the civilian market, it is perfectly acceptable to the manufacturer if the consumer orders a car that he does not truly need, but in a zero-sum market, it is necessary to buy optimally. To tweak the system to solve this problem, it would be desirable to station representatives of a central body with the combat unit. These representatives, with understanding of the state of the industrial situation, could approve or modify orders. To promote understanding of industry and pull in the field, cross-training operational and logistics officers with the industrial base more extensively than today would be helpful in such a contingency.

The second key difference is that, in wartime and not peacetime, there is a responsive, reactive enemy who may launch attacks on key nodes. At a low level, lean production has effective methods to mitigate damage from a conventional strike. The use of parallelism in the line reduces single points of vulnerability. While mass production might have floor value concentrated in expensive, large, static machines that are difficult to defend, lean production's value centers of people and light, more mobile machines are easier to protect. Disruptions – from natural disasters to labor strikes – also occur in the civilian market, and lean production has evolved effective ways to deal with them that are applicable to the wartime case. A fire that shut down the sole source for a key Toyota part for months only stopped production for four days due to the flexibility and resilience of lean. Even though Toyota has arranged 99.96 percent of deliveries on time, keeping enough stock to deal with the other 0.04 percent is imperative. In other words, Toyota does a rational calculation of where the balance between carrying cost and risk lies, and sizes stockpiles to meet it. This calculation has not failed to account for larger-magnitude events such as the Aisin fire or the Tohoku earthquake. Enemy attack against key nodes may well make such low late delivery rates as 1-in-2,500 impossible, and may make single-point failure events like Aisin far more likely, which will change the calculation of the balance to favor higher stockpiles. However, this does not necessitate revisiting the basic idea that flexibility and responsiveness are more effective than stockpiling.

There are reasons to believe that specific sectors and nodes of a lean economy might be more vulnerable to attack than the corresponding sectors and nodes in an economy based on classical mass production principles. One such area is communications. A system that relies on "pushing" preplanned products is necessarily less reliant on communications than a system that relies on feedback. A system that delegates more power to the level of the floor is potentially more vulnerable to sabotage. While these are of concern, it is possible to mitigate most of the risk by making small tweaks to contemporary practice without compromising lean ideas. The final step of distribution, from heads of the fixed supply chain to mobile units, is also potentially vulnerable to enemy interdiction. One might argue that only a stockpile-based approach could deal with the potential for interdiction. Stockpiles far forward, however, are vulnerable to the same enemy attacks and interdictions; many times in World War II, before the advent of precision strike, attacks on forward ammunition magazines and fuel dumps were damaging to operations. To fill a "pull" request from the front, then, a tweaked system might transmute the request into a larger one. The size of the new request would be determined by statistical formulae that help to ensure, based on long-term interdiction trends, that no less than the right amount will arrive. Even if a large excess amount is sent forward, the lean system is still dominant over the classical mass system in this regard.

Third, the nature of the mission in wartime is essentially one of rapid capacity expansion. In peacetime environments, any capacity expansion is slow, while in a mobilization production must rapidly increase. This difference is so fundamental that it is necessary not only to compare a lean system to a mass system, but also to determine the basic feasibility of expansion under a lean system while under enemy attack. Generally, there is reason to believe rapid capacity expansion in a lean system would both be feasible and more capable than a similar expansion in a classical mass production system. A large part of this is due to lean production's emphasis on the flexibility of the human worker, instead of on particularly large or unwieldy machines. Despite potential massive need to re-shore production, facility build times from the civilian market indicate that expansion would be possible in about three years in almost all sectors.

Further, some proposed methods to hide from enemy conventional precision strike – revetment, underground burial, dispersion, and mobility – would be much more feasible under a lean production regime than under a classical mass production regime. In most industries, there would be relatively simple ways to combine these measures to make the cost exchange ratio for (b) (5) conventional missile attacks unfavorable. In a few industries such as the semiconductor industry, there is cause for optimism on methods to protect these systems, but further research is required.

In terms of raw materials for wartime capacity expansion, the United States and Canada are well-endowed, from iron to rare earth materials to energy resources; combined with the neutral block, there would be sufficient supplies of almost all materials. The greatest bottleneck that such an expansion might face would be of skilled manpower, for refining and other key tasks, especially oversight of lean plants and participation in a lean, "pull"-based system operating from the military front. Since lean production relies on human flexibility, training a lean worker can take years. Research into lean training in schools and ways to determine who is amenable to lean methods, then, is advised for the present. Raising a cadre of top-level lean consultants who may facilitate lean conversion and expansion is also a relatively inexpensive move that should be undertaken in the near future.

In summary, there is cause for optimism about the future of mobilization. Many of the problems that occurred in World War II mobilization were the result of an inherited civilian production philosophy which was mismatched to demand. Due to the evolution of civilian industry, a future mobilization structured according to the principles of "lean" philosophy would be far less likely to feature these problems. Even under conditions of severe enemy attack, lean principles would facilitate mobilization within a relatively short time period. The greatest bottleneck would be not any specific industry but rather manpower. There are ample topics for further research and current investment relevant to the problem of quickly alleviating the manpower bottleneck in time of need.

INTRODUCTION: PREPARING FOR MODERN WAR

Inspired partly by a series of war games held by the Long Term Strategy Group (LTSG) during 2011-12, this study begins from the premise that two nuclear-armed powers such as the United States and (b) might engage in a large-scale, non-nuclear conflict, and that such a conflict would entail prolonged fighting and require the mobilization of civilian industrial capacity to support the war effort on both sides. This is not to say that nuclear weapons would not be used in a future war that concerned vital national interests and featured a significant conventional imbalance. (In the Cold War, nuclear war was conceivable in Europe, and it may become conceivable again during a conflict in South Asia or over the Russian Far East, for instance.) But in a future conflict between the United States and (b) (5) the interests at stake may not warrant risking strategic nuclear exchanges. Because the US-(b) macroeconomic balance may be comparable by 2030-40, the war could be prolonged, and industrial planning would become important. In a protracted, conventional conflict, popular support in both countries would facilitate the conversion of civilian industrial capacity for military goods. Such conversion would be part of the total commitment necessary to defeat a similarly sized enemy – i.e., in a military and economic contest in which production merely at a replacement rate would not suffice. Rising tensions and an observable (b) (5) force build-up would provide some degree of warning, allowing the United States to prepare for mobilization before the outbreak of violence.[1] This study is largely aimed at addressing how the United States might prepare for a defense mobilization to prevail in a large-scale, intercontinental, conventional war.

Before turning to this subject, it is first necessary to outline in slightly greater detail the nature of the envisioned conflict. Based on LTSG's recent war games, beyond the assumptions listed above, two additional assumptions can be stipulated:

- For the United States the only usable civilian industrial capacity would be located in North America and Western Europe because (b) (5) would be vulnerable to (b) (5) political pressure and/or attacks.

- Escalation to reciprocal conventional strikes against key homeland industrial facilities is possible.[2] The United States may launch these strikes with bombers and cruise missiles,

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[1] This report does not make explicit assumptions about how long this period is. This line of research aims to determine how long a mobilization would take. Eventually, a reciprocal understanding of (b) (5) mobilization timing will help to determine (b) (5) actions that are triggers for mobilization steps, and the steps of the longest lead time will be particularly important triggers. The failure of the British to respond to triggers before World War II ("The Ten-year Rule and Disarmament" (British National Archives) or Harrison, "Resource Mobilization," *Economic History Review*) indicates the importance of having as quick a mobilization as possible.

> in addition to using conventionally armed ICBMS; (b) [redacted] would be primarily limited to strikes using conventionally armed ICBMs.[3] Due to the cost advantages of aerial delivery over conventional ICBMs, the United States might prefer to launch attacks by means of bombers and cruise missiles. Geography also permits the United States to use smaller ICBMs.[4]

The conventional ICBM threat does not change the essential nature of mobilization, as effective defenses exist. Modern US ICBMs have a circular error probable (CEP) of about 100 meters.[5] This CEP limits the power of conventional ICBMs. Many targets would be too small to be efficiently attacked by such a weapon, which is far more expensive per destruction delivered than a bomber.[6] To destroy some targets would require many conventional ICBMs – e.g., it would take

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[2] This report does not contend that such attacks will occur. Many argue that such attacks are indistinguishable from nuclear first strikes. However, deterrence may be sufficiently stable so that one missile launch does not provoke retaliation. Separated conventional and nuclear missile fields might also provide assurance.

[3] The US may have such capacity due to (b) (5) [redacted] geography and strong regional allies, while (b) [redacted] may not due to (b) (5) [redacted] geography and mediocre relations with weak Latin American countries.

[4] Mobile US conventional ICBMs could, with infrastructure improvements, be launched from (b) (5) [redacted] (b) [redacted] miles from coastal (b) (5) [redacted] industry, while (b) (5) [redacted] launch sites are (b) (5) [redacted] miles from American industrial centers. However, potential Russian Far East launch sites are only (b) [redacted] -(b) [redacted] miles from American industry concentrations. This underscores the importance of the role of Russia.

[5] This refers to the Minuteman III, Peacekeeper, and Trident II (Sublette, *Nuclear Weapon Archive.)* They use inertial guidance as well as star-sighting ("Trident Missile Factfile," BBC). Remarkably, very little of this error is caused by drift in the inertial guidance system; instead missile separation, initial position, and reentry effects contribute to inaccuracy. See Sublette, *Nuclear Weapon Archive* (page on AIRS) and Gronlund, "Depressed Trajectory SLBMs." Some argue that much more accurate conventional ICBMs are feasible (Casey, "Response to 'The Obama Bomber,'"), and even though GPS may be unusable given enemy space denial capabilities, the general point stands. More accurate ICBMs would tend to make revetment and burial less viable and mobility and dispersal more important, but may not change the overall conclusions of this study.

[6] Casey, "Response to 'The Obama Bomber,'" notes that a conventional ICBM would be far cheaper than a nuclear ICBM because of a cheaper warhead and a possible digital guidance system. The Falcon 1 civilian space launch vehicle, a missile body, costs $7 million (Malik, "SpaceX…") to lift 1,400 lbs to LEO (Honan, "Falcon 1…"). In comparison, a B-2 costs $135,000 per hour (Trimble, "US Air Force…") A 30-hour mission from CONUS to and from the target would cost about $5 million (without counting tanker re-supply and attrition), with a much greater payload. Concepts like (b) (5) [redacted] are still expensive, as launch costs per kilogram are still extremely high (space Transportation Costs, Futron). A breakthrough in missile technology would be necessary to make conventional ICBM cost competitive.

16 such missiles to be very likely to destroy the George Washington Bridge.[7] A facility may be protected if its value is dispersed enough so that the cost of the missiles to destroy it is greater than the cost of the damage. Intra-plant utilities, which were highly vulnerable from attacks by large numbers of low-accuracy weapons in World War II,[8] are already dispersed in this manner: A single missile impact cannot cause more damage to the grid than the value of the missile.[9]

Consider also the precedent set by Japanese wartime industry, dispersed from large factories, which were vulnerable to high-explosive attacks. This was largely ineffective because it was slow, and because massed firebombing attacks could destroy many of the dispersed facilities at once.[10] Dispersal could defeat smaller numbers of expensive munitions, however, especially since managing a dispersed network may be much more feasible due to digitalization. Soviet nuclear war planning suggests an additional approach. The Soviets designed revetments for equipment in the crisis period, to shield equipment from nuclear effects and make it usable after a war.[11] Importantly, since Soviets were not planning to produce during the crisis, they did not need to frequently move machines in and out of revetments. For the contingency posited in this study, machinery would need to move into revetments on very short warning. Still, the basic concept has value. Finally, burial, while expensive,[12] takes advantage of the high cost of the missile. Destruction of a buried target requires exact positional knowledge and then ground penetration.[13] Smaller buried targets may be difficult to locate precisely enough to destroy, incentivizing small plant size. Still, a large number of missiles will eventually destroy a high-value target.[14]

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[7] A direct hit seems to be necessary to destroy a bridge. (See Boyne, "Breaking the Dragon's Jaw," Sublette, *Nuclear Weapons Archive* and "Operation Carolina Moon," GlobalSecurity.org.) Only about ¼ of the CEP area is filled by the bridge, so the overall hit probability is very roughly 1/8. Then sixteen missiles will have about a 90 percent chance of hitting the bridge.

[8] See USSBS, *ETO Summary*, 11.

[9] Attacks with (b) (5)) may be mitigated by shielding, and may be ineffective against underground or indoor utilities as may be found at an industrial facility.

[10] See USSBS, *Pacific Summary* and Herman, Ch. 18.

[11] Yegorov, *Civil Defense: A Soviet View*, pg. 179-195 and particularly pg. 189.

[12] Nuclear weapons may make burial cheaper. Even "dirty" nuclear explosions in suitable geological formations may leave tolerable radiation after a few months, as tested in 1961. See "Project GNOME."

[13] Attempted kills by destroying all access points can be defeated by a large number of phony access points.

[14] A revolution in ICBM accuracy could have most impact here. If one weapon does not have sufficient penetrating power, it is necessary to aim with subsequent weapons at the hole caused by the first. High accuracy is needed to hit this hole: to have a reasonable chance of destroying the Iranian complex at

If kernels of extreme value cannot be economically dispersed, these kernels might be made invulnerable by mounting them on trucks or railcars.[15] For those factories that would be vulnerable to vibrations, however, constant mobility may be unfeasible. Periodic movements of the railcars could be sufficient, as denial of space may make real-time target location difficult and time-consuming.

Evidently, many measures can be taken to protect key industrial nodes against conventional ICBMs, so this weapon does not require a complete rethinking of production. Protective capability would be greatly and critically advanced if a missile's rough impact zone could be identified while the missile were in midcourse, allowing far more warning time to protect exposed value. Overall, given adequate preparations, the United States has little to fear from reciprocal (b) (5) [redacted] attacks on domestic industrial facilities. But what would constitute adequate preparations? The rest of this study is aimed at addressing that question.

Fordow, it could take up to 75 heavy Israeli bunker busters (Long, "Can They?"). A low CEP may make this approach much more practical for ICBMs.

[15] If a kernel is large but light, an aircraft may be viable; if it is not susceptible to vibrations, a ship may be viable. These modes may help to decrease response time and delivery throughput time, by manufacturing en route.

THE MASS PRODUCTION SYSTEM

All production systems for military goods have been rooted in ideas for producing civilian goods. For most of history, production for military and civilian goods has been based on a system known as craft production.[16] Craft production was dependent on very skilled artisans, who in many cases had been apprentices since childhood. They had achieved mastery of a wide variety of production processes, and were capable of producing small numbers of goods to order. This system, however, was incapable of producing goods in large volumes.

The industrial revolution separated goods into two categories. Very simple goods could be produced by unskilled labor. Because there was no sequence of operations, assembly, or interchangeable parts, this was distinct from the more meaningful organized production system and philosophy of mass production.[17] For other goods, such as early cars, the same craft production techniques were still followed.[18] Since the manual and primitive mechanized techniques that were in use were quite imprecise, there was no standardization of components. There was a requirement for skilled artisans to do adjustment work, to ensure high standards of quality.

Military production drove the development of production technology. For most applications, goods might be locally fabricated as well as locally repaired by skilled craftsmen. Repair of military equipment might be necessary in the field, without skilled craftsmen, from available parts.[19] One solution was interchangeable parts: If parts could be freely swapped, service would be far simpler. This level of precision was beyond the reach of human craftsmen, however skilled, and so the means of production became more mechanized and more sophisticated.[20] The idea of interchangeable parts was essential to the idea of mass production.

Before Henry Ford, an automobile was a luxury vehicle built to customized order; Ford sought to make it more affordable.[21] Rather than building each car to custom design, which required the owner to have staff mechanics for repairs,[22] Ford would build the car using interchangeable parts.

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[16] A great resource for craft production is Hounshell, *From the American System.*

[17] See Hounshell, *From the American System.*

[18] See Womack, *The Machine*, ch. 2.

[19] Hounshell, *From the American System*, 23 and 33.

[20] Hounshell, *From the American System*, ch. 1.

[21] Womack, *The Machine*, ch. 2.

[22] Womack, *The Machine*, 23.

This would reduce costs by reducing the need for skilled labor: There would not be a highly paid craftsman for adjusting, but rather a low-skilled worker to assemble perfectly-fitting interchangeable parts.[23]

Costs had been radically reduced, thanks to Ford's new system of production and unvarying design,[24] before the famous conveyor belt. The conveyor belt reduced the time workers spent moving, reducing man-minutes to assemble a chassis from 750 to 93.[25]

The successes of the resulting system of mass production are well known. Mass production is coarse, working on the basis of long-term demand forecasts. To mass production, "the market" will, in a certain quarter, request a certain supply that has to be met. The individual customers are not considered – in other words, a mass system views the world as a monopsony. Philosophically, mass production does not pixelate to the level of a specific customer needing a specific product at a specific time. Instead, it works on the coarse level of markets and quarters.[26]

These assumptions were well-fitted to demand in the Model T era. The offering was so limited that Henry Ford remarked, "Any customer can have a car painted any colour [sic] that he wants so long as it is black."[27] To be able to respond to any consumer request, Ford only needed to stock one model; his production space was of dimension one. Monopsony was compatible with meeting the basic shape of customer demand for Ford's products. Forecast reliability was not hugely important, since any overshoot in production could be sold in the next quarter, as the Model T's basic design was roughly static, and it was Ford's only major product for 18 years.[28]

Ford's idea was flawed, since customer demand was not only for one mostly constant product, but for an entire family of products with yearly introduction of new models. The upstart General Motors (GM) was able to offer such a blend, and rapidly gained Ford's market share, almost forcing Ford into bankruptcy. It was difficult to adapt Ford's production machinery, which was

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[23] Womack, *The* Machine, 31.

[24] Womack, *The Machine*, 28.

[25] Arnold, *Ford Methods*, pg. 139

[26] For a far deeper exploration of the characteristics of mass production, Womack, *Lean Thinking* and Womack, *The Machine* are highly recommended.

[27] Ford, *My Life and Work*, 72.

[28] Sole Model T production lasted from 1909 (Ford, *My Life and Work*, 72) to 1927 ("Model A Vehicle History.")

not designed to be flexible enough to change models. However, eventually Ford adopted largely the same concept as GM, including model changes and customizability.[29]

While industrial capabilities had advanced, mass production philosophy had not changed. The companies still did not cater to the individual consumer, but focused on the market demand as a whole, despite the newfound multidimensionality of planning. It was necessary to stock a large array of types ready for the customer to choose from, rather than just one type of car.

Since changing the production line from one type of car to another was expensive, the companies tended to produce in large batches. They would produce an entire period's forecasted demand of a certain model, then an entire period's forecasted demand of a second model, and so on. However, there were manifold disadvantages of this approach. With an increased product family, the size of a batch of any unique product decreases, increasing total forecast error. It was possible to forecast Model T sales, since for one large number volatility relative to production was relatively low. The absolute exposure to volatility over many small batches was far higher.

Cases of underproduction became more frequent. Cases of overproduction also became more frequent, with more severe consequences. Previously, overproduction might be sold off with the next quarter's identical batch; now the overrun faced obsolescence due to continual model change. While selling the overrun at a discount was better than not selling at all, this was still a waste for the manufacturer. Thus, the assumptions about monopsony remained intact, even if new market conditions introduced problems that were not present in the early Fordist days.[30]

The resulting inefficiencies were implicitly acceptable due to the strategic situations of the companies involved. The market was big enough for all contemporary large companies to survive, even with suboptimal practices. Even if ideas to improve efficiency had surfaced, a company not in crisis has a strong incentive to follow the path of least resistance instead of making painful changes.[31]

The needed profit was fixed according to corporate strategic intentions, and the cost was fixed due to the tendency to follow industrial practices according to the path of least resistance. The price, the sum of the needed profit and the necessary cost, was thus given.[32] Since different companies had comparable prices due to comparable resources, the system was stable.

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[29] Hounshell, *From the American System*, ch. 7.

[30] For a more in-depth discussion of the inefficiencies that plagued the mass system, Womack, *Lean Thinking* and Womack, *The Machine* are highly recommended.

[31] Even today, when the road map for cutting costs is well market, a company usually must be in crisis to make these changes. See Womack, *Lean Thinking*, 250. Companies may evolve some of these characteristics, however, in certain settings. See Appendix Six of this report.

[32] This clever formulation is due to Ohno, *Workplace Management*, ch. 6.

LEAN PRODUCTION PRINCIPLES

Mass production, in this form, advanced through World War II (for the performance of mass production during the war, see the following section of this study, "Mass Production in World War II").[33] Without challengers to the system, the lack of ideas, pressure, and political will to reform might have resulted in mass production's survival. There was a demand for cars, and the entry cost for new ideas was very high.

Challengers to the system, however, did emerge from a foreign market. In Europe, mass production ideas had been adopted and were widespread,[34] but a Japanese firm, Toyota, found itself in desperate straits in the late 1940s. The sewing machine company had begun to make autos in the 1930s, but was co-opted by the wartime Japanese military.[35] Emerging from the war with bombed-out facilities, Toyota aimed to overtake the American car firms to be the biggest in the world.[36] Marginal improvements to the American mass production system were insufficient due to high entry costs and the cost of sophisticated equipment.[37] Instead, Toyota enacted Taiichi Ohno's radical ideas,[38] creating a new "lean" production system.[39]

The two critical philosophical assumptions of mass production, of the reliability of forecasts and of the utility of the monopsony model, were in lean philosophy reversed. Forecasting tended to increase error. Mass production would "push" its forecasts on the customer, regardless of the shape of demand. The lean theory of "pull," in lieu of push, called for production only in response to a "pull" of an item by the next step in the chain.[40] Ohno was inspired by seeing pull at work in

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[33] This section is a highly abstract treatment. For a better practical understanding, the reader is referred to Womack, *Lean Thinking* and Womack, *The Machine*.

[34] For some coverage, see Womack, *The Machine*, 230-235.

[35] Womack, *The Machine*, 48.

[36] Ohno, *Toyota Production System*. 3.

[37] Womack, *The Machine*, 50.

[38] This was at great tribulation: there was a great strike that led to the ouster of the president. Womack, *Lean Thinking*, 233.

[39] Popularization of this term is due to Womack, *The Machine*, who in turn cites John Krafcik (13). Again, it is critical to note that, while elements of lean production were introduced in other places, Toyota systematized the system and added new ideas to it. See, for instance, the discussion found in Appendix Six of this report.

[40] For more discussion of pull, see Womack, *Lean Thinking*.

the supermarket.[41] Since many goods were perishable, analogous to extremely rapid obsolescence times, keeping large inventories was unviable. Instead, the supermarket would keep a record of exactly what was bought by consumers on a given day, and replenish it nightly.[42]

Ohno's profound idea was that what works for milk and eggs should work just as well for cars and airplanes, both inter- and intra-factory. For instance, Toyota has adopted this pull system for service.[43] Mass service centers, with most of their inventory full of long-time stocks of simple goods, had difficulty responding to more unusual orders. Using pull enabled much more responsive, smaller inventories of common goods, which freed up room for esoteric goods, tied the responsive factory to the rest of the chain, and reduced the need for forecasts. As opposed to mass rates of 98 percent service in seven days, this pull system achieved 98 percent service in two hours.[44]

Of course, one must have enough on hand to be able to meet any likely demand for that day, to prevent sell-outs. But, if daily demand is reasonably well known, it is possible to get close to that amount almost without running out ever.[45]

The idea of "push" is related to the conception of the market as a monopsony, viewing the market as one customer to be matched by prediction. In the era of one-dimensional demand, this might have been workable, but today demand is quite multidimensional.[46] It is necessary to supply the right number of every type to the right place at the right time, matching the precise shape of demand on a finer level. The conception of monopsony is obsolete.

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[41] Ohno, *Just-In-Time*, 16-18.

[42] This replenishment would come from a distribution center. If the distribution center kept a stockpile itself, this would be an incomplete application of lean. Instead, the distribution center might itself pull to replenish itself directly from the farms or factories, constituting a healthy lean system.

[43] See Womack, *Lean Thinking*, ch. 4.

[44] Womack, *Lean Thinking*, 86.

[45] A one-day forecast has a much tighter error distribution than does a forecast for a quarter. Merely a small stockpile can be kept to meet all possible daily "pulls," replenished by production. A much larger stockpile must be kept for 90 days, since revision in production schedules to accommodate demand may be impossible. Some companies keep no inventory at all, where the goods are built to order, for example Dell (Sheffi, *The Resilient Enterprise*, or "Dell's Make-to-order….") Customizability is greatly enhanced: there are 1.4 million choices for operating system and graphics card, for a low-model desktop (Dell Precision T1650; *Dell Official Site*). Without 3D printing, this model can only work in industries where people are willing to wait for the good to be transported.

[46] For example, there are 16 Chevy models, and the Chevy Sonic has six trims. (*Chevrolet Official Site*). There are 12 types of Lexus, nine basic Lexus IS models, and 43 packages (not counting color).

This responsive pull system clearly requires smaller batch sizes. In mass production, these batch sizes would have been uneconomical, as the die changes necessary to end an old batch and start a different one were time-consuming and expensive. In other words, the economic order quantity (EOQ) was very high. Long-term forecasting enabled high EOQ, while entrenched use of EOQ reinforced the tendency to forecast. Toyota developed ways to improve the change time to circumvent this obstacle to a pull system; to depress the EOQ.[47]

Furthermore, Toyota realized the inadequacy of the formulation price = cost + profit. Like the Western manufacturers, Toyota's profits were fixed by corporate strategy, but Toyota needed lower prices to gain market share. Since cost was the variable, a more accurate formulation was cost = profits – price.[48] Cost was reduced by a step back to first principles: Ohno started with the sole goal of the producer, to deliver value to the consumer.[49] Many industrial steps, termed *muda*, do not add value from the customer's perspective, and they can be reduced with flexibility as the guiding mechanism. Ohno enumerated seven different categories of waste,[50] and Womack added the eighth.[51]

1. Defects. Effort spent fixing defective products is wasted. To stop defects, mass production relied on inspection late in the process. Since deeply buried errors tended to be hard to find, this method often failed to catch defects.[52] Still, fixing these deeply buried, propagated errors was very expensive, and required many skilled man-hours.[53] Furthermore, identifying and solving the root cause was difficult at such a distance, so

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[47] A "perfect" lean system would have an EOQ of size one. The Toyota goal was SMED [single[digit]-minute exchange of dies], or that any switchover should take less than 10 minutes. See Womack, *Lean Thinking*, 352.

[48] This is the history of this formulation; it is more efficient in the general case as well.

[49] Again, for a broader and deeper discussion of value, the reader is referred to Womack, *Lean Thinking*; Ohno, *Toyota Production System*; Ohno, *Workplace Management*; and Ohno, *Just-In-Time*.

[50] See Ohno, *Workplace Management*, ch. 6.

[51] Womack, *Lean Thinking*, 355.

[52] GM's mass Framingham plant had 130 defects per 100 cars. Toyota Takaoka had 45 (Womack, *The Machine*, 80).

[53] Some mass plants spent 20 percent of plant area and 25 percent of man-hours on rework (Womack, *The Machine*, 57).

the errors might recur. Classical mass production developed statistical error-catching methods that were helpful, but did not solve the basic issue.[54]

Lean production attempts to avoid this waste by identifying and resolving the problem as it occurs, to minimize recurrence and propagation. Mass production workers rarely stopped the line and could be punished for doing so; only senior managers could stop the line.[55] Contrarily, lean assembly workers are empowered and encouraged to call for a response by fix-it teams. If a spot fix cannot be found, the entire line stops.[56] As the process became better and the workers became more experienced, stoppages tend to become very rare.[57]

2. Overproduction. Mass production responds to forecast inaccuracy by producing more goods than needed. These are either sold at a discounted price or, failing that, discarded. In other words, the forecast is "pushed" onto the customer, whatever the true demand looks like. Lean production reduces exposure to forecasts with a new concept known as "pull." To avoid overproduction, something is only produced when it is called for by the subsequent step.

3. Inventories. Classical mass production tended to schedule production according to long-term forecasts, minimizing the number of changeovers of the production line to maximize batch size; that is, the company might produce all of Product X for a quarter and then all of Product Y for a quarter. Since production was not temporally matched to sales to consumers or the demand of subsequent steps, there were large inventory build-ups at all stages to ensure that the customer's demand could ultimately be met.

   However, inventory is expensive. Carrying cost is estimated at 25-55 percent per year.[58] The total carrying cost for an item could add very substantially to the cost in a

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[54] For instance, Motorola invented the six sigma toolkit (Snyder, *Lean Six Sigma).* Yet, as the quality theorist Deming understood, statistical techniques are maximally effective when the line worker is empowered to make corrections, and there is a culture of making quick changes to the line. (Troncone, "Dr. W Edwards Deming"). The tools have limited utility when not involved in a lean framework; that is, lean is more basic. This paper views lean as a philosophy and statistical process control as a methodology, albeit an important one, but with far more technical applications than lean.

[55] Womack, *The Machine*, 79.

[56] See, for instance, "Toyota Quality."

[57] Womack, *The Machine*, 56-57.

[58] See *Methodology of Calculating Inventory Carrying Costs*. This number does not linearly increase with time: deposition and retrieval costs, for instance, are fixed.

value chain with many stockpiles.[59] There is also the challenge of obsolescence. In case of a model change, inventories can at best be modified, requiring rework, or at worst become valueless. Even in the case of cans, the painting scheme often becomes obsolete.

If forecasts were always accurate, there would be far less need for inventories. Everything produced during a quarter would be sold, leaving no inventory at the end of a production period and greatly mitigating the cost problem. However, since forecasts are known to be inaccurate, inventory becomes "just-in-case" for deviations from the forecast. Lean production sees the forecasts as the source of the waste, and instead seeks to minimize exposure to forecasts. Hand-in-hand with the idea of "pull," then, comes the converse to "just-in-case," "just-in-time."[60] Rather than maintaining large inventories as a contingency for inaccurate forecasts, supplies are delivered just as they are "pulled" by the next step.

To be clear, lean does not decree mindless cuts to inventory. Inventory still has proper roles. As discreteness of transport prevents continuous shipment of parts, some inventory must be kept to last the company between shipments. Furthermore, the prediction of arrival of a truck from another company is still an inevitable forecast that requires just-in-case stocks. However, this dependence can be mitigated by working with suppliers to ensure on-time arrival. [61]

For further discussion about how successful just-in-time can be, and worst-case scenarios, see Appendix Seven of this study.

4. Movement/Motion. Any unneeded movement in the plant is wasteful. This was often a major problem in mass factories. Machines were often located in "process villages," grouping all the machines responsible for any particular task.[62] While this improved mass production metrics of co-location of similar human resources and large machines efficient at high volumes, it led to movement of parts all over the plant. The convoluted parts chain tied up energy to move, and the confusion made an intra-plant just-in-time schedule impossible.

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[59] Womack, *Lean Thinking*, 38-43 maps the value stream for a coca-cola can. The total time spent in static inventory (not in transit) is about 35 weeks.

[60] This term is due to Ohno, who also notes that "exactly-in-time" may be a better rendering of the idea.

[61] At Porsche, 20 percent of parts arrived over 3 days late, 30 percent of shipments had the wrong number of parts, and 1 percent of arrived parts were unusably defective (Womack, *Lean Thinking*, 194). Only 0.04 percent of parts delivered to Toyota by first tier suppliers are defective, and only five parts per million are defective. (Womack, *Lean Thinking*, 239).

[62] See, for instance, Marchwinski, *Lean Lexicon*, 76-77.

To reduce confusion and add visual control, lean production implements “single-piece flow,” which groups production in cells. Under this system, an assembly moves in a smooth path from one station to the adjacent next station, radically reducing intra-plant movement. This idea of a smooth, short path for a product is very intuitive; lean restores the complicated “spaghetti charts”[63] to the more rational system. A deep understanding of single-piece flow is necessary for actually implementing a lean system inside a factory. For the purposes of this paper, a superficial understanding, centered on the value lean sees as inherent in simplicity, will suffice.

5. Transportation. Transportation clearly adds costs of energy and mobility assets. Lean also sees transportation as wasteful for a deeper reason: It makes pull more difficult, since pull works best if the supply chain is rapidly responsive to demand.[64] While the gain in decreased labor costs might outweigh the cost of transportation, long supply chains themselves are a greater hidden cost that must be accounted for. Then, systems where links are far apart, in the worst case systems that depend on multiple transoceanic shipments, tend to be seen as wasteful.[65]

6. Waiting. Labor time spent waiting is clearly wasted. This was a major problem in homebuilding, for example, when, two-thirds of a schedule was spent either reworking defects or waiting for the next set of specialists.[66] Classical mass production keeps large and expensive buffers to avoid waiting; lean production instead makes operations flow more smoothly.

   To actually reduce waiting time, lean has developed a concept and methodology known as takt. For the purposes of this study, a deep understanding of takt is unnecessary. One

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[63] A term from Womack, *Lean Thinking*, pg. 104/352.

[64] See, for instance, Womack, *Lean Thinking*, pg. 334-5.

[65] Womack, *Lean Thinking*, 333 and 245. Despite popular conceptions that Toyota massively imports into the US, only 30 percent of Toyota’s North American vehicles are imported (Vales-Dapena, “Toyota to Export…,”) while Klier, *Who Really Made Your Car?*, claims that most parts for transplant factories are domestically sourced.

Even so, Womack, *Lean Thinking*, 245-246 suggests that “oceans and leanness are usually incompatible,” which implies that Toyota should create mutually independent firms on all continents, and that the current level of imports is unsustainable. Womack, *Lean Thinking*, 284 claims: “…many Japanese firms need to acknowledge that the fundamental logic of lean thinking requires production to be conducted near the customer and that many tasks long conducted in Japan simply do not make sense there. … The idea that low-volume, build-to-order, domestically oriented Showa rather than high-volume, export-oriented Toyota is the future will require some getting used to.”

[66] Womack, *Lean Thinking*, 51.

important technique, however, is to avoid to the extent possible the overspecialization of labor.

7. Overprocessing. Generally, overprocessing refers to doing more work than is necessary, whether by redoing what work has already been done or doing work with machines that are more complicated than necessary. An example is the system that Pratt & Whitney used to make turbine blades.[67] The expensive grinding machine would have destroyed the blade in case of direct contact, so an expensive encapsulation fluid had to be applied to and removed from the blade. The solution to this overprocessing problem was to replace the expensive machine with several simpler machines, to avoid the need for encapsulation. What is optimal for one point in the process is not necessarily optimal for the process as a whole.

8. Design. "Design of goods and services which do not meet users' needs."[68] This is akin to overproduction at the level of design. Individual goods can be produced in quantities in excess of demand, but at relatively low cost compared to design of entire products that are ill-matched to demand. Then, pull should apply to design as it applies to production.

   Design inherently requires forecasts. Then, lean seeks to minimize the length of the forecast to enhance accuracy. To avoid designing products that fail to meet customer needs due to inadequate forecasts, lean aims to minimize the throughput time between the drawing board and full production. For instance, the Honda Accord was developed in four years, while the GM-10 took seven years to introduce the first model and nine years to introduce the last model.[69]

Generally, lean production responds to all these waste areas with flexibility. To support such flexibility, Ohno reinvented the role of the person in production. This role in fact became one of Ohno's two key tenets, written as autonomation, or automation with a man in the loop. [70]

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[67] Womack, *Lean Thinking*, 176-177. For more discussion about how lean production views design, see Appendix Six of this report.

[68] Womack, *Lean Thinking*, 355. Womack does not quite discuss the meaning, so this is the author's interpretation. The author also adds the failure to design goods and services that *do* meet users' needs to this category.

[69] Womack, *The Machine*, 108 & 110.

[70] Womack, *Lean Thinking*, 347 offers: "Transferring human intelligence to automated machinery so machines are able to detect the production of a single defective part and immediately stop themselves while asking for help. This concept, also known as *jidoka*, …" Ohno, *Just-In-Time*, 31 cites Sakichi Toyoda's self-checking looms. However, this leads to reinvisioning the role of people as flexible and as thinkers,

Autonomation initially reacted against keeping unnecessary manpower, where one man might solely be responsible for watching one machine and waiting for it to err. Much time was spent waiting since errors were rare. Lean first tried to make the machines better able to catch errors.[71] More philosophically, a person was made responsible for more than one machine. This began a trend to see the value of a "blue-collar" worker as mental just as much as physical.[72]

This reaction is not so relevant in today's developed economies, although in developing or undeveloped economies it may have some utility.[73] More relevant to the United States is the reaction against the idea of overautomation – taken to its extreme, the idea of lights-out manufacturing. Many Western mass producers in the 1970s and 1980s made clear that their goal was the elimination of direct labor.[74]

This was a product of the vision of the worker as deriving value from his hands, not from his head. One metric that demonstrates how little mental value the system thought blue-collar workers had was the extremely low suggestion count per worker.[75] The division of labor between white-collar workers, who were thought to have mental value, and blue-collar workers, was very distinct.

In lean production, by contrast, a person is inherently capable of both manual and mental work. The entire process of suggestion and continuous improvement is mental, not physical.[76] People

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which is discussed extensively in Ohno's books. Lean does not see the elimination of labor as a good objective and instead highly values smart application of labor.

[71] This technical solution is known as *poka-yoke* in Japanese.

[72] See, for instance, Ohno, *Workplace Management*, 124.

[73] In (b) circa 1990, (b) employed 1.6 million workers to make 0.6 million cars, as opposed to Japan's 0.5 and 13 million, respectively, a productivity difference of 70 times. (Womack, *The Machine*, 268-269). In 2005, First Automobile Works claimed about 140,000 employees ("Fortune Global 500…") on production of about 1 million units ("First Auto's…"). Perhaps, (b) is using labor in this capacity.

[74] See Finkelstein, "Case Study…"

[75] Porsche had 0.06 suggestions per employee per year, which became 12 suggestions per employee per year after the lean transformation. Japan, by contrast, had 29 suggestions per employee. (Womack, *Lean Thinking*, 200). The vast majority of these suggestions are adopted (Robinson, "The Role of Front-Line Ideas."

[76] The breakdown of this division goes both ways: "white-collar" engineering and management resources are moved physically much closer to the floor, and encouraged to take "gemba walks" (see Rosenthal, "Walking the Gemba") to examine or help. In some cases, effective senior consultants partake in moving the machines (numerous examples in Womack, *Lean Thinking*). This setup closely parallels that described

work best, then, when respected. This is hugely important: Half of the below-listed productivity gains are from this process of suggestions.[77]

Lean production has delivered enormous results. Generally, within two to three years of implementation, a lean process delivers increased labor productivity by a factor of four, cuts the number of errors delivered to the customer by a factor of four, decreases in-system inventories by a factor of *twenty*, and decreases production throughput time[78] also by a factor of *twenty*.[79]

Many companies, Toyota the most well-known example, have risen to prominence or become revitalized due to these methods. Womack, *Lean Thinking*, gives detailed analysis of the lean transformations of many companies. Many of the winners of the Shingo Prize, an award that was given to 15 of the most lean organizations, are illustrious companies;[80] likewise, the list of companies that lean experts consider to be exemplary has many well-known names.[81] Indeed, a majority of companies describe themselves as implementing lean.[82] The difficult times of the recession have led yet more companies to adopt lean production.[83]

The unconvinced or interested reader is referred to Appendix One of this study.

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in Rich, *Skunk Works*, 46 and 115: the low distance between the brain trust and the floor was key to their success.

[77] Womack, *Lean Thinking*, 27 describes that half of the improvements generally be achieved instantly upon full adoption of lean – this is known as the *kaikaku* – and the next half by worker-inspired and -led continuous improvement – *kaizen* – in the next two or three years.

[78] Presumably, this term is synonymous with the term “lead time” also used on Womack, *Lean Thinking*, 27. This also presumably refers to operations within a factory, since lean does not improve transoceanic shipping times (as opposed to waiting times within the port, perhaps).

[79] Womack, *Lean Thinking*, 27.

[80] See “The Shingo Prize Recipients.”

[81] See “The Superfactory 20…”

[82] See Davidson, “Lean Manufacturing Helps Companies Survive Recession.” A total of 61 percent of companies described themselves as implementing lean principles.

[83] See Davidson, “Lean Manufacturing Helps Companies Survive Recession,” and Engardio, “Six Sigma is Out…”

MASS PRODUCTION IN WORLD WAR II

The archetypal mobilization example of the United States in World War II represents a test of a production system that is still used today.[84] By the time of World War II, mass production methods had been widely disseminated in some industries, especially in the auto and auto parts industries.[85] The United States had twice the population, 2.5 times the industrial production, and 3 times the war potential of Germany. Likewise, the United States had twice the population, 6 times the industrial production, and 12 times the war potential of Japan.[86] American potential multiplied more than four-fold between 1900 and 1938;[87] much of this may be attributable to mass production. Mass production's many successes need not be further extolled here. Instead, its shortcoming, relating to the basic suboptimal assumptions behind mass production, should be examined.

Mass production was designed to run under a monopsony with long periods between buys. These assumptions were perfectly synchronized with contemporary government thought. The buyer of all defense goods was the US government,[88] a single body, which bought in quarterly if not yearly chunks based off long-range forecasts. Roosevelt, for instance, issued one notable forecast, calling for 60,000 airplanes in 1942 and 125,000 in 1943.[89]

Again, this philosophy was well-suited for the era of the Model T, where a "special case" of market demand was amenable to those philosophical assumptions. Likewise, prominent lean proponents claim that World War II is this same "special case."[90] It is the central contention of

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[84] For war production pre-WWII, see Appendix Five of this report. For other countries in WWII, see Appendix Four of this report.

[85] The aircraft industry was still craft-based; see Herman, 114-115 for instance.

[86] See Kennedy, *The Rise and Fall of the Great Powers*, pgs. 320, 322, 517-518.

[87] See Kennedy, *The Rise and Fall of the Great Powers*, pg. 322.

[88] Technically there were the War Department and the Navy Department, but a two-buyer system of this sort with low overlap is very similar to a one-buyer system.

[89] See "War Production," PBS.

[90] See Womack, *Lean Thinking*, 158, which is downright puzzling. Regarding Pratt & Whitney: "Work-in-process, travel within the production system, rework in the test department at the end of production, and managerial complexity all increased but engine output increased even more, and the latter was the only important consideration during the war." This directly refutes many of the principles that the authors try to advance elsewhere in the book. Making an engine is not free: it consumes valuable human, engineering, and material resources that could be used elsewhere in the zero-sum wartime economy. The problems that are correctly noted tend increase human, engineering, and manpower costs that must be carefully allotted.

this section that the demand in World War II did not meet these conditions; rather, adherence to a production system optimized for these conditions was extremely inefficient.

Theoretically, the model of the federal government placing quarterly or yearly buys was artificial. The War Department was a convenient representative to place long-term orders, but it was not the ultimate consumers. The consumers were, rather, combat units in the field. The production system should not be measured by its ability to respond to War and Navy Department requests, but rather by its ability to supply combat units in the field.

The root of dissonance of mass production's forecast with military operations is in the inherent unpredictability of military demand. First, design evolves too rapidly to predict. In the Model T era, a single item was produced for long periods of time. In wartime, due to feedback from the theater, design changes were abundant. This destroyed the efficiencies of the Model T system even in plants making only one model to avoid die changes. It is extremely challenging to predict the necessary characteristics of any unit for war with an inherently unpredictable enemy, and any initial design risks units ill-suited to the environment. The historical record speaks most clearly for airplanes.[91] In World War II, the Army Air Corps began the war armed with the P-36, P-39, and P-40, failing to match the Japanese Zero plane. Even if initial units are adequate, the enemy may innovate to reverse the tables. The P-80/F-80 in Korea was soon outclassed by the MiG-15, necessitating the introduction and development of the F-86.

Thus, development of types and models in wartime is an iterative improvement process pulled along by combat events.[92] Direct changes to make the plane more suited for combat in turn require spirals of more changes, all under conditions of high pressure.[93] For instance, the 1938

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[91] Although airplanes are the best-documented failure, there are other examples: the original Mark 14 torpedo design was defective (see Newpower, *Iron Men and Tin Fish*). In some cases, feedback from the theater went unaddressed: shipbuilders kept painting ships, despite the known tendency of paint to burn; on some ships the sailors were employed to chip off the paint. (Hornfisher, 206-207) These examples were likely abundant; a part of the problem was likely failure of these modifications to propagate to the manufacturers, as a result of the separation between the industrial complex and the field army.

Formations had organic field modification capacity, in part due to relative simplicity of devices and similarity to civilian devices. Still, this came at the cost of tooth-to-tail ratio. The repair capacity could have been further back in the distribution line. It is unclear if this organic capacity exists today, with such complex weapons. Certainly, there is a massive, resource-draining manpower commitment to this sort of thing: See Powers, "Number of Air Force…"

[92] Use of the word "pull" is intentional. Events in the field demand improvements.

[93] Designs still spiral today, with the F-35 (725+ design changes; see Axe, "Trillion-Dollar Jet…") and F-18E/F (see Trimble, "Boeing's Fighting Comeback.") Today, anticipating needed second- and third-order changes is easier.

F4U Corsair’s design was modified 3,000 times.[94] The B-29 was with great difficulty engineered to have many gun turrets, which were promptly removed upon adoption of incendiary bombing.[95] It took time and many model changes to resolve the P-38’s diving problems.[96] The early P-51 did not have long range capacity.[97] Mass production’s response was to produce a fixed design, as it knew how to do, and then perform rework on the planes as necessary.[98]

Changing a line to account for model change is different from changing a line between models, as the former requires no reversal. However, both invalidate the idea that production is a simple affair of making as much of one item as possible. Indeed, obsolescence costs, a great weakness of the post-Fordist mass production system, become an even greater a problem in wartime production, due to the accelerated technology development cycle.

Related to obsolescence, long supply pipelines delayed introduction of new technologies. It took four months before the proximity fuse was first used.[99] Word of the revolutionary system did not spread quickly enough through the complex distribution system for fuses to be rapidly disseminated; as a result, VT weapons were unavailable at Santa Cruz. Likewise, the F6F Hellcat was not combat-deployed until August 1943, despite the first production flight in September 1942 and deliveries of production aircraft before 1943.[100] While the first production F4U Corsair flew on 25 June 1942, it was not deployed in combat until February 1943, missing almost the entire Guadalcanal campaign.[101] These vast delays of introduction into service cost lives.

A larger problem than rapid design evolution was adequate re-supply. Again, prediction of demand for existing units is extremely difficult to predict. Peacetime demand variability is rooted in factors of economics and customer preferences, for which prediction tools exist. However, demand variability in wartime is a function of action by the malicious and responsive enemy. Forecasting the specific enemy actions which effect consumption is nearly impossible.

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[94] See Hawks, “Best Fighter Planes of WWII.”

[95] Herman, *Freedom’s Forge*, 327.

[96] See Hawks, “Best Fighter Planes of WWII,” and

[97] See Hawks, “Best Fighter Planes of WWII, and Allen, “The Development of the P-51B/C.”

[98] Herman, *Freedom’s Forge*, 23.

[99] See Jennings, “The Proximity Fuse.”

[100] See Andrews, “F6F Hellcat.” Perhaps part of this was training crews and maintainers, but it also seems like the eight month figure probably includes the pipeline.

[101] See Gustin, “Chance Vought F4U Corsair.”

Planners realized that plans only formed a baseline forecast of expected enemy behavior, but deviations were to be expected. The supply chain needed not only to supply the expected demand of the planners, but also to supply an envelope of actions to meet a wide variety of contingencies. This envelope took the form of stockpiles. Some stockpiles were carried by the infantryman, to meet an envelope of tactical contingencies; others were held in a whole chain of forward and rear supply bases, leading all the way back to the factory in the United States.

The sole point of flexibility, the staff schedule planners, were very far both in distance and in time from the point of variable consumption. During Operation Torch, it took six months for a new order from theater to arrive.[102] Since the campaign was only six months, no off-plan supplies could regularly arrive in time; huge reserves were required. By early 1944, the War Department required 90 days of notice to fill requisitions.[103] During the later phase of Operation Dragoon, fill times were between 90 and 180 days.[104] At Okinawa, the fill time was 120 days.[105]

In many cases, massive contingency stockpiling backed by a rigid industrial base failed. Unlimited resources could support an arbitrarily large envelope of contingencies that deviated from the baseline. However, since the Allies did not have unlimited resources, shortages arose when the ground situation pulled out of the envelope of acceptable deviation from the planners.

For instance, the planners' envelope was exceeded by the unexpected intensity of hedgerow warfare in Normandy. Heavier-than-anticipated German resistance ruined the plan for a quick breakout.[106] The reduction of Caen, planned to occur on the first day, took months.[107] To deal with this heavy resistance, especially in hedgerow country, it was necessary to use more munitions than were held in stock.[108] Then, detrimental rationing of ammunition began.[109]

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[102] See Dworak, *Victory's Foundation*, 161. Only two to four weeks (Dworak, 125) was crossing the Atlantic. By later in this campaign, the time was down to 60-75 days (Dworak, 124-125), better but still extremely long. It is worth noting that shipments could be expedited to sail as early as 20 days after receipt of requisition (Millet, *Army Service Forces*, 64), but expediting one shipment was likely to delay others (see Womack, *Lean Thinking*, 107.)

[103] See Dworak, *Victory's Foundation*, 357. Note that this order was filled from stateside supply depots, not factory production; anything that the depots lacked was unfilled.

[104] See Dworak, *Victory's Foundation*, 425-426.

[105] See Frank, *Victory and Occupation*, 71; only 30 days of this time was transoceanic shipping. Note that this re-supply period was far longer than the Okinawa campaign.

[106] See "Overlord Revised," *Center for Military History*.

[107] See Eisenhower, *Eisenhower at War* pg. 210 for instance.

[108] See Adams, *The Battle for Western Europe*, 49.

Likewise, early enemy resistance at Anzio was heavier than expected, forcing the Allies to assume the defense.[110] The large supply investment in tank ammunition was not useful; the envelope for use of howitzer ammunition was exceeded, resulting in very severe shortages. It was necessary to use tanks as makeshift artillery, inclining the tanks to elevate the guns. This was suboptimal: Although the result was adequate, it made the campaign more costly.[111]

Despite these inadequate performances in many cases, stockpiling was costly. A basic criticism was that the shipping situation was zero-sum, and shipping spent maintaining the War Department's standard of a 75-day stockpile[112] – over 20 percent of the length of Allied ground combat operations in mainland Europe – was not spent delivering items experiencing shortages.

Furthermore, maintaining stockpiles was expensive. Stockpiles are vulnerable to attack, thefts or accidents. An accidental chain explosion in Normandy destroyed 1,500 tons of ammunition.[113] Stockpiles proved vulnerable to battlefield reverses, as at the Battle of the Bulge.[114] Supplies in the Persian Gulf suffered more losses to theft than to U-boats.[115] Even while Axis air and artillery capability was quite limited, at Palau stocks were still destroyed.[116]

Skilled manpower[117] requirements to deposit, sort, inventory,[118] guard and deliver ammunition were high. The ratio of combat troops, the deliverable combat power,[119] to service troops was

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[109] See Mayo, *The Ordnance Department*, 250.

[110] For more on this incident, see Dworak, *Victory's Foundation*, 344.

[111] In terms of lean production, this is known as overprocessing: using a unit that is more complex than necessary.

[112] See Ruppenthal, *Logistical Support of the Armies*, 247.

[113] See Mayo, *The Ordnance Department,* pg. 251.

[114] See Cole, *The Ardennes*, 266.

[115] See Millet, *Army Service Forces*, 66.

[116] See Leckie, *Helmet for My Pillow*, 295-296.

[117] Even in World War II, sortation required highly skilled troops: see Dworak, *Victory's Foundation*, 240.

[118] Critical items were inventoried daily (Dworak, *Victory's Foundation*, pgs. 369-370). Flux measurement, combined with periodic audits, seems like a much cheaper approach.

[119] This is a slight simplification, as service forces have emergency combat power. At the Battle of the Bulge, the 3rd Armored Division and 45th Infantry Division service forces were used defensively and

very high: There were about four service troops per every combat soldier.[120] Cost tended to spiral: Ammunition sorters needed food, which required transportation and security, and vehicles, which required maintenance. These maintainers, in turn, required food and transportation. By weight, service forces consumed half of all supplies.[121] To support a limited combat presence, it was necessary to have an extremely large and expensive rear area footprint.

Commanders understood the cost of rigid stockpiles and the advantages of flexibility and responsiveness, and attempted to invent systems to move the decision power closer in location and time to the field. During the Okinawa campaign, despite the 120-day re-supply request period from stateside (see above), Gen. Buckner was able to pull re-supply vessels from staging areas at Ulithi, Eniwetok, and Saipan as called for by the situation on the ground.[122] Given the stage of the war, the many ship-hours spent waiting were acceptable; the effort, however, was made much more expensive. Scarce capacity was presumably spent preparing shipments planned until L+210, October 1945, instead of focusing on immediate and non-contingent tasks.[123]

Indeed, the fundamental limitation of the efforts of these commanders was that they were only working with a part of the supply chain; the production base was not on board with their efforts. For instance, Patton's gas shortages in the Third Army dash across France were not caused by a

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offensively (*Spearhead in the West* and Foster, *Overview: The 157th Infantry at Reipertsweiler,*) while Marine service forces were used in combat at Chosin (Butler, "70 Miles of Cold, Hard Road.") However, the total combat impact is likely quite low.

[120] Dworak, *Victory's Foundation*, seems to estimate the ratio at about three to one. Kirkpatrick, *An Unknown Future*, notes that, while there were 45,000 service troops in the 'slice' of a 15,000 man infantry division, only 76 percent of the men in the infantry division were combat troops. If only men in companies, batteries and troops are counted as "combat," this yields a ratio of more than six service troops per combat soldier.

This ratio, termed the tooth-to-tail (T3R) ratio, receives study today especially since re-supply in places like Afghanistan is so expensive. To the extent that "combat soldiers" has meaning in a counterinsurgency campaign, depending on how contractors were counted, between 12 percent and 40 percent of soldiers were combat (McGrath, *The T3R*).

[121] Dunn, *The Soviet Economy and the Red Army*, 61 , lists the total daily burden of (an American) divisional slice as 541 tons: 100 tons rations, 117 tons service material and replacements, 144 tons of fuel, and 180 tons of munitions. If rations, service material, and fuel are used in about equal proportions by combat and service troops, the combat forces consume 180 tons of munitions and 20 percent of the other 361 tons, for a total of about 250 tons.

[122] See Frank, *Victory and Occupation*, 71.

[123] See Frank, *Victory and Occupation*, 71.

shortage of gas in Normandy, but by a bottleneck in delivery of gas to Patton's front.[124] By heroic efforts, the Red Ball Express attempted to re-supply Patton, but was a failure because of lack of trucks, beyond the maximum exigency of the envelope for truck supply.[125] If heroics with available assets were insufficient, the clear solution would have been simply to produce more trucks. The 6,000 trucks used[126] were about a week's production.[127] Even accounting for delivery times,[128] a responsive industrial base would have been able to alleviate the Red Ball Express's difficulties within three weeks of the beginning of the problem, which took three months to resolve during the war.[129]

COSTS AND WASTE

Besides the problems resulting from reliance on forecasting, there were also problems resulting from large implicitly accepted costs. Again, in mass production, profit was regarded as structural; some costs were implicitly acceptable; and price was variable.[130] The government allowed companies to take a fixed fee, cementing corporate thought about price.[131] Cost was not the utmost concern for the government; that is, they were willing to pay relatively high prices. Corporate mass production, then, was well matched to government values.

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[124] See Grassi, "Refuel on the Move," or Ryan, *Bridge Too Far*, 70.

[125] For a general history, see US Army Transit Museum, "The Red Ball Express, 1944." While some sources mention the lack of drivers (see US Army Transit Museum, "The Red Ball Express, 1944" or Grassi, "Refuel on the Move," this seems implausible: at this crucial juncture, finding a few thousand men who could drive a truck seems eminently doable. While mechanics might have been in shortage, this problem would have been solved by simply more trucks.

[126] See US Army Transit Museum, "The Red Ball Express, 1944."

[127] See Motter, *The Persian Corridor and Aid to Russia*, 143.

[128] Said ship capacity would have been available, if necessary by reducing shipments of other goods; the true bottleneck for the entire theater was these trucks. This is an application of the lean idea of *takt*. A several-stage process, with the end goal of creating deliverable combat power, should have synchronized flow through each step. The laggard, in this case the link from the beach depots to the combat forces, is the best point to apply effort.

[129] See US Army Transit Museum, "The Red Ball Express, 1944."

[130] While Ford did dramatically reduce the cost of bomber assembly, beyond the steady state point of mass production wastes in the categories detailed below were implicitly acceptable.

[131] Herman, *Freedom's Forge*, 102-103

Government thought about cost, however, was mistaken. The dollar cost is a function of manpower, materials, and machine time; all of which are zero-sum in wartime conditions. In the case of World War II, manpower and material were used efficiently enough to spin victory from macroeconomic superiority, albeit at an increased cost of lives. This victory was aided by bad Axis decisions: For instance, Hitler mistakenly deployed the Me 262; the Germans built capital ships and not submarines; the Japanese did not commit battleship reserves to Guadalcanal. The next enemy may not make such mistakes. Implicitly accepted costs in World War II may be categorized in the same way that wastes in lean production were categorized.

1. Defects. Mass production effectively reduced defects in non-consumables such as trucks and airplanes by testing and rework, which was a huge commitment of labor.[132] For expendable goods such as munitions it was impossible to test every round. The haphazard quality control of World War I,[133] when a full 25 percent of artillery shells were duds,[134] was replaced by a more rigorous approach, led by the famous quality theorist W. Edwards Deming. Deming taught statistical methods that could weed out quality problems while keeping the proportion of ammunition expended in tests low.[135]

   While quality rates improved, there were still many defects. Between 5 percent and 30 percent of bombs dropped on Germany were duds.[136] Even today, estimated defect rates are about 10 percent.[137] During recent tests, Taiwanese missiles failed at a rate of 32 percent, while South Korean missiles failed at 20 percent.[138] In the 1998 Afghanistan raid, 75 missiles were fired at terrorist targets; six of the missiles allegedly crashed in Pakistan.[139] While current US standards for cluster munitions are for less

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[132] The rework rate for B-29 engines was 50-60 percent (Herman, *Freedom's Forge*, 317). The British still delivered defects, resulting in 1400 useless trucks during the key phase of the Red Ball Express. Ryan, *Bridge Too Far*, 70.

[133] See *Investigation of Defective Ammunition* in many places, for instance pg. 32-33

[134] See Connolly, "Legacies of the Great War."

[135] See Godfrey, "The Adequacy of Prior Controls."

[136] See Crossland, "Unexploded Bombs in Germany" and Busé, "World War II Ordnance."

[137] See Busé, "World War II Ordnance," or "Murphy's Law: Frugal and Humiliated."

[138] See "Murphy's Law: Frugal and Humiliated." It is unclear what type of Taiwanese missiles were fired, but the South Korean rate is drawn from SM-2, Harpoon, and Sea Skua missiles.

[139] See "Background on the Cruise Missile," Williams, "The Missiles of August – Part II," "Pakistan Test Fires Babur Cruise Missile," and "A 2nd Tomahawk Dud is Reported." This 6/75 rate does not count missiles that misfired, crashed into the sea, crashed into Afghanistan before the targets, or failed to explode.

than 1 percent defects,[140] the Israeli 2006 campaign in Lebanon had defect rates as high as 40 percent.[141] The cost of defective cluster ordnance is not only post-war casualties and cleanup, but by an increased supply footprint due to proportionally increased ammunition requirements.

2. Overproduction. Inherently, the approach of keeping large envelopes to deal with any case will leave large inventories left over at the end of the conflict. These represent production capacity that could have been spent making goods that would have shortened the war.

   During World War II, large numbers of Purple Heart medals were minted in preparation for the planned invasion of Japan. About 500,000 were surplus after the invasion was cancelled. As a primer in the problems of stockpiles, 125,000 of them were lost, prompting an order for more Purple Hearts in 1976, and then the 125,000 were found. They are still awarded today.[142] Since the medal's "shelf life" is long, eventually most will be distributed. However, there is still cost: In 1985-1991, the medals required work to refurbish, and over (b) [redacted] of the medals were found to be un-refurbishable.[143] The warehouse also has cost. The zero-sum character of the wartime economy adds more waste, however: The skilled labor and strategic materials might have instead been used to make weapons to reduce the eventual number of disbursements. The Purple Hearts for postwar conflicts might have instead been produced in a time of less critical need.

   There were many leftover munitions. In 1947, the British detonated 6,800 tons in TNT equivalent of surplus depth charges on the island of Helgoland.[144] This was a very large proportion of depth charges expended by the British during the entire war.[145] The

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[140] For a sober analysis, see, for instance, "Unexploded Ordnance (UXO)."

[141] See Rappaport, "IDF Commander."

[142] See Giangreco, "Are New Purple Hearts Being Manufactured?" and Schogol, "Are Purple Hearts from 1945 Still Being Awarded?" Why were medals minted so far in advance of Operation Downfall (1 November 1945?)

[143] See Giangreco, "Are New Purple Hearts Being Manufactured?"

[144] It's not entirely clear that the explosion was all depth charges. The best sources claiming this are "Destruction of Helgoland" and "Helgoland Fortress Will Be Blown Up." Also see McDonald, "Helgoland."

[145] Llewellyn-Jones, *The Royal Navy and ASW*, 34 claims that 23 tons of depth charges were required to sink a U-boat. Fewer than 601 U-boats were sunk by British warships (see Helgason, "U-boat Fates"),

surplus TNT, then, was a very high fraction of production. TNT itself was a scarce quantity, and many decisions that potentially cost lives were taken because of TNT shortages; labor was wasted.

3. Inventories. As detailed above, the extensive inventories kept were very costly.

4. Movement/Motion. There is little historical record of this intra-factory waste, although cases are known.[146]

5. Transportation. Since the war was being fought in places far removed from most of the production facilities, some transportation was inherently necessary. Transportation reduction by moving production closer to the front lines was underemployed. Plants set up in Persia for shipment to Russia were successful.[147] If the plants were successful in Iran, why was this not possible in France, to alleviate the problems of the Red Ball Express?

   Waste of transportation occurred in other cases.[148] St. Louis-based Timken was making axles for Chicago's Yellow Coach, but Yellow Coach was making axle components for Timken, adding a net of 600 miles of transportation. This transportation consumed valuable gasoline, demanded more road maintenance, and also added time.

6. Waiting. While there were surely many examples of intra-factory waiting, as is inherent in any mass production process, these are unlikely to be well documented. There were also many examples of inter-factory waiting. One notable example was at the B-29 factory in Wichita, where the planes had to sit on the tarmac waiting for engines.[149]

7. Overprocessing. Again, intra-plant historical details are difficult to find. However, in the case of the B-24, Ford ordered a new mill that did 42 operations in 35 minutes.[150] This sounds like a classic "monument" – an oversized machine that overprocesses and

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which gives an upper bound of about 14,000 tons. Morse, *Methods of Operation Research*, 63 claims that 614 depth charges and 700 ahead-thrown charges were used monthly in 1944. Even if all of these depth charges were the heaviest type (see "Britain ASW Weapons,") the Helgoland explosion was the equivalent of over a year of depth charge production.

[146] One example is provided by Pratt & Whitney: Womack, *Lean Thinking*, 158.

[147] See Motter, *The Persian Corridor and Aid to Russia*, 140.

[148] See Herman, *Freedom's Forge*, 255.

[149] See Herman, *Freedom's Forge*, 307-308.

[150] Herman, *Freedom's Forge*, 230.

makes flow impossible, and is best replaced with smaller machines, like Pratt & Whitney's blade grinders.[151]

8. Design. Design of unwanted goods was a frequent occurrence, for instance the SB2C Helldiver, the new dive-bomber.[152] The prototype Helldiver was flown by Curtiss in December 1940. While it had many problems, these were resolved to make the plane relatively fit for combat, at the cost of spiraling weight by 42 percent. The plane was first used in combat in November 1943.[153]

   Carrier skippers preferred the older SBD Dauntless: According to procurement officer Cdr. Riley, "the SB2C was so tricky to fly, compared to the SBD, and so hard to maintain that the skippers of the new carriers preferred to have the old SBDs. We had quite a battle forcing the SB2C down their respective throats." Pilots who flew both aircraft usually preferred the SBD.[154] The commander of VB-17 claimed that "the SB2C offered little improvement on the SBD…the SBD would be my choice."[155] Besides the damaging combat and service losses, it required a tremendous waste of factory, engineering and design resources to develop the program, all of which could have been employed on a multitude of other aircraft projects.

In a classical mass production system, wastes of these types are expected. The underlying dynamic of military production in wartime is similar to the post-Model T dynamic of peacetime civilian production. Then, the same peacetime mass production shortcomings would be expected to fall short in the analogous wartime situation. This is supported by evidence. A wartime system to resolve these shortcomings, yet takes into account important differences, can be devised.[156]

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[151] See Womack, *Lean Thinking*, 176-179.

[152] See Guttman, "Curtiss SB2C Helldiver."

[153] Tillman, *SBD Dauntless Units*, 87, claims that SB2C-armed Allies might have lost at Guadalcanal without SBDs.

[154] Tillman, *SBD Dauntless Units*, 11.

[155] See Guttman, "Curtiss SB2C Helldiver."

[156] See Appendix Three of this report.

LEAN AND FUTURE WAR

WARTIME MODIFICATIONS TO LEAN

The central idea of this study is that the assumption of long-interval monopsony and variability of price, which animated mass production systems in peacetime and wartime, are at least as misplaced in military mobilization scenarios as in the civilian market. Flexibility and pull, so successful in the civilian market are indeed applicable to the mobilization case. Mobilization is not non-stop continuous production like the Model T era; rather, flexibility is crucial.

Military goods for wartime are not inherently different from goods for peacetime. While lives depend on quality and reliability in wartime goods, so do lives depend on jet engines that are made with lean. Broadly, then, the same principles apply to defense mobilization systems.

However, in narrow strokes there may be potentially important modifications to lean ideas. To determine these ideas, it is essential to consider how military production in wartime differs from the case for which lean production was developed, civilian production in peacetime.

- A large-scale war, unlike civilian production, is zero-sum: The front could use arbitrarily many resources. Then, the constraints on manpower, raw material, and machine time resources become acute.[157] Resources must be allocated correctly to avoid waste.[158] Then, lean's waste reduction ideas, by pull and by other means, are more critical, and lean tenets become more important. Still, some issues may arise as a consequence of the zero sum economy.

    1. There may be a problem of allocations. Some aspect of the economy will "max out" in a large enough war, reaching a limit and necessitating priority

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[157] The problem needn't be all of these, just one of them. The American World War II bottleneck was materials. Like the British, the US economy never reached its manpower capacity. Machine tool capacity utilization in most industries was only on the order of 72 hours a week (Office of Progress Reports, *Capacity Utilization*). This seems to suggest that the biggest bottleneck was raw materials.

Lean aims to resolve bottlenecks with takt. All stages – here, manpower, machine capacity, and resources – should be synchronized to avoid waiting. Then, takt would advise manpower allocation to mineral extraction, and flexibly designed tools to be allocated to refining. Takt would solve a manpower shortage by automation, and takt would respond to a shortage of tools by increased used of manpower and tooling shifts from mining.

[158] Allocation may not sound very lean, since it is like forecasting. However, allocation in response to real-time demand is necessary. Allocation also takes place in even lean systems in the form of capacity planning. Lean guides that capacity planning have the goal of flexibility, but still these decisions must be made.

assignment. The economy may not be able to meet all of the demands placed upon it. While lean ideas can lower the footprint of the military mission and decrease the need for supply capacity, lean is not capable of magic, and it may be impossible to meet the demand for supplies for some operation.

This is an unresolved problem for lean like mass. However, a more straightforward system, with rapid responses to requisitions and lower throughput times, will make it easier for decision makers to do their job with the maximal information; that is, they will be able to anticipate and avoid these problems when planning grand strategy.

2. Some pull may be "bad." In peacetime, an order is neither good nor bad. It is irrelevant to the manufacturer whether the customer actually needs the car he ordered, so long as he can pay. In wartime, however, a pull from the field might be unnecessary, or suboptimal. The industrial base should only respond to the pulls considered most crucial by grand strategy.

   To encourage judicious pull, there should be representatives of industry and of a national production priority board on the ground, best if integrated into combat units so that they have a very good grasp of the situation. The officers or teams that make the requisitions should also have components that deeply understand grand strategy and industrial capacity. Today, many people are cross-trained in strategy, combat operations, and distribution, but there is a production understanding gap.[159] The military might increase programs to build cross-functional skills, and plan to mobilize discharged officers and men who have taken industry careers. Either of these means can sort requests, helping to keep the economy operating on the best track.

- In military environments, unlike civilian peacetime production, an intelligent adversary will attempt to hamper production. Likewise, this has several consequences:

  1. Low stockpiles could backfire, as disruptions become more likely due to enemy attacks. This will change the optimal stockpile size. In peacetime, lean production sets stockpiles to the optimal buffer size necessary to deal with uncertainty in life, resulting in a far smaller stockpile than those of mass production systems. The numbers may change as uncertainty is enhanced by an enemy, but the same basic logic holds. While too small stockpiles make a supply chain vulnerable to small-scale disruptions, overly large stockpiles are too expensive for the risk.

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[159] The original mission of ICAF was to connect industry and the military, but lately they seem to have shifted focus to logistics and strategy (see "History of ICAF Series.")

The presence of an adversary makes formerly low-probability events, like single-point factory disruptions, become far more likely. Stockpile size may increase as the optimum changes, depending on specific industry conditions. However, this increase must be very limited. Stockpiles would need to be unrealistically large to respond to all possible contingencies.

Ideally industrial vulnerabilities should be reduced; increased flexibility will enable easier restoration of supply. The Germans found out that flexibility is necessary to complement stockpiles; in some industries, their stockpiles lasted long enough to get them between plant repairs and production reconstitutions.[160]

2. A pull-based system inherently depends on communications, unlike push systems where feedback is less important. Re-supply is in accordance with demand, which must be communicated. The presence of an adversary may make this need a liability.

   In peacetime, this is no liability, as any disaster that impairs these links will impair the means of production themselves: Communications are not a bottleneck. Blocking, interception and spoofing of orders are of little concern in peacetime. Denial-of-service attacks, the primary means of blocking, are temporally limited. Interception of orders has limited impact. Spoofing would soon be discovered, and its perpetrators heavily punished.

   In wartime, however, blocking, reading, and spoofing all become far more pressing. A belligerent that can contest cyberspace might not refrain from interfering with logistics. Requests might be blocked from exiting the field by jamming or destruction of communications systems; interception of requests could be useful intelligence; spoofing of requests might confuse the means of production and distribution and potentially prevent delivery of the correct items.

   While it is likely impossible to jam a theater against a relatively low bandwidth,[161] the other two categories are of great concern. They might be solved by advances in cryptography, or development of production capability closer to or in the theater. It would also always be possible to revert to a backup preplanned schedule if necessary. The eventual re-supply decision must be made with the information at hand; in the worst case, re-supply will be according to the best guess, or plan, of the planners. In other words, with

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[160] See USSBS *ETO Summary*.

[161] To reduce bandwidth, it would be necessary to use complicated and pre-agreed symbology.

regards to this vulnerability, pull dominates push. In the worst case, pull simply reverts to push; otherwise pull performs better.[162]

3. Vulnerability to industrial espionage or sabotage. Lean production gives broader process knowledge and more decision-making power to the floor worker, due to enhanced trust in his capabilities. In peacetime, espionage and sabotage by infiltrated workers is not a pressing concern. It is unlikely that business competitors would resort to human espionage. Foreign governments might, but lean production's heritage did not build in this concern. Toyota did not have big technological secrets that would be worth stealing.

   In peacetime, cyber theft is far more prevalent than manned espionage. Since information is recorded in both mass production systems and lean production systems, lean production is not comparatively more vulnerable to information theft; while the potential for cyber espionage or sabotage certainly deserves further research as to mitigation, lean does no worse than mass here.

   In wartime contingencies, espionage and sabotage do become concerns. However, lean production has inherent protections against this type of attack. To be successful, such an attack would have to be very highly professional. The saboteur or spy would have to be very skilled, since engaging in the lean dynamic requires very much communication and discussion. The success of Israeli airport security's emphasis on engagement shows that this is difficult.[163] Key plants might have discreet personnel trained to recognize suspicious interactions. However, this is not foolproof; there have been successful government moles who have been engaged daily.

   Large-scale sabotage is less of a concern in lean production than in mass, as lean attempts to eliminate expensive and vulnerable "monuments" that might be attacked. In lean production, one saboteur's damage capability would be very low, given the value lost in the saboteur's capture.[164]

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[162] If a pull-based system is used despite enemy interception capability, this may not be true, but it is beneficial to give operators the capability to use pull if merited by the situation.

[163] See Totten, "Forget the 'porn machines.'"

[164] Cyber damage may be different: for instance, flash drives could be surreptitiously inserted. It is arguable that lean is more vulnerable since the average floor worker is likely to have more access to computers, but measures can be taken against this (the DoD presumably is successful here). At the minimum, computers might be designed with flash drives only physically accessible by specially cleared personnel.

Espionage is potentially a challenge. Still, while a lean worker may know more than a mass worker, one source on the floor is only of so much value to an intruder. In cases where individual workers acquire tremendously useful technological knowledge, there are measures common to lean production and mass production. Rich, *Skunk Works* details measures like the two-man rule, random security searches at night, and non-marked papers. While these measures may impair productivity, they may be necessary to solve massive espionage problems. Again, lean dominates mass. While a compartmentalized system takes on mass production aspects and becomes inferior, it is still superior to mass production due to retained lean elements.

4. It may be difficult to deliver goods. In peacetime, delays may happen due to traffic. This may be mitigated in many ways, but overall the goods will almost always get through. However, in wartime, there may be some attrition due to interdiction. The enemy might use anti-access area denial capabilities to destroy ships in transit; tactical airpower or short-range rockets might destroy vehicles in transit from supply bases to combat units.[165] This challenges the idea of pull, which is predicated upon the ability to deliver exactly the right parts exactly the right time.

   If the delivery throughput time is low, it might be possible to respond to loss by simply dispatching a new cargo. This requires keeping a larger stockpile of the goods in the intermediate stockpiles, but this is an acceptable loss in a system with high loss rates due to enemy action. If delivery throughput time is high, shipping new goods may be unacceptable. Here, it is possible to intentionally send more than is needed; the amount sent over the required to be determined statistically, based on the desired percentage assurance.

   While inefficient and unadvised by lean production in peacetime, this is a necessary adaptation to fit the environment. Adapted lean production still dominates mass production. Randomness inherent in statistics represents uncertainty, and additional uncertainty in the system increases the safe buffer size. However, the abundance of other wastes in mass production would dramatically increase the amount sent over the necessary amount.

5. In certain cases, the presence of knowledge about exactly where a certain good is may be bad. While mass production might not have kept track of exactly where each good was,[166] lean production is far more likely to do so. An enemy

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[165] This indeed puts an added premium on reducing the throughput time, as the longer the throughput time – particularly the longer the product is stopped while onboard a truck – the greater the likelihood of interdiction.

[166] See, for example, Mayo, *The Ordnance Department*, 251.

   might potentially determine and attack those distribution units which are carrying crucial goods. In mass production systems, if the shipper cannot determine where the crucial goods are, the enemy certainly cannot; this may be possible in lean production. The adversary could determine this through espionage.

   Lean production might respond by mixing the goods over more vessels. This is inefficient in peacetime, as it increases entropy; however, it may be necessary in wartime. In war, diversification and even limited randomization may be essential to protection.

6. Mass production has much waste; perhaps some of it is accessible momentarily in an emergency. An emergency reduction of waste might enable one to remain running in an emergency, despite lower regular-case efficiency. That is, built-in wastefulness may lower production in good times, but raise it in bad times due to temporary measures to meet exigencies.

   It may be crucial to always have supply of some commodities. If the commodity can be stockpiled, keeping emergency reserves seems like a better approach than building in waste in capacity. Stockpiling capability is limited in the energy industry, but here instead a minimal level of reserve energy capacity permits response to the most urgent production demands. Rather than building in waste, which takes effort and is uncertain, maintaining more capacity than necessary may be a better approach, to assure the minimal level.[167]

7. Specific factories might be vulnerable to attack, perhaps enhanced by use of lean production instead of mass production. This is discussed below.

- The nature of the task in a military mobilization scenario is different from that of peacetime. Peacetime market demand generally moves relatively slowly, so any expansion in productive capacity is slow. In this contingency, production must be rapidly expanded, to fill lost supply sources in East Asia and to rapidly increase the production of military units.

  The problems of zero-sum and vulnerability to enemy attack were soluble by re-scaling of strategic priorities and acceptance of delays, respectively; the discussion above only attempted to identify better ways. To respond to this difference, it is necessary to demonstrate that expansion is possible at all, because there is no minimally acceptable "worst case" scenario.

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[167] This is the basic concept behind backup electric generators. Many institutions and people feel that some level of electricity is necessary. As a buffer for grid downtime, they keep reserve capacity rather than reserve electricity.

WARTIME EXPANSION

This paper breaks expansion into three major categories – raw materials and energy supplies (including machine tools necessary for increasing production); mobility platforms, weapons, and transportation capacity; and manpower capacity.

RAW MATERIALS AND ENERGY SUPPLIES

In terms of raw materials, the United States and Canada have supplies of most raw materials, from iron to rare earth materials to energy resources; combined with the neutral block, there are sufficient supplies of almost all materials.[168]

Allied capability to produce refined goods is a function of industrial capacity, capacity resilience, and capacity expansion, not deposits. The early Soviet atomic program was hampered by lack of uranium reserves.[169] The Allies, will not face such problems, since expansion of raw materials is a relatively simple task. Many of the most crucial minerals, like iron, have lower import rates, greatly simplifying the expansion problem. Even for these minerals, expansion may be needed as overall production grows. In the worst case, new mines would be required.

Mines are either open pit or underground. Open pit mines are far more prevalent.[170] With sufficient manpower, an open pit mine can be extracted by men with only basic equipment. This is a relatively quick process with high yield potential.[171] Modern mines, for efficiency, use heavy machinery, but this is still relatively quick to expand. The Mountain Pass rare earth mine, once the source of most rare earths globally, closed in 2002 due to environmental concerns.[172] It filled with water 100 feet deep, and had no equipment.[173] While reopening was planned in October 2009, permits and funds were only secured in December 2010, and mining only started in January

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[168] This clearly demonstrates the importance of Latin American and African allies. The US can influence and force favorable dispositions of these countries' mineral reserves, analogous to the World War II Iran intervention. Please see Appendix Eight of this report for additional information on world mineral reserves.

[169] See Rhodes, *Dark Sun*, 70.

[170] Open pit mines make up 85 percent of minerals overall: over 97 percent of ores (but only 61 percent of coal). See Hartmann, *Introductory Mining Engineering*, 11.

[171] For instance, see Swineford, *History and Review*, on the first Michigan iron mine.

[172] See Venton, "Rare-Earth Mining Rises Again in United States."

[173] The depth of the mine was 400 ft (Juetten, "Rare Earth Mining at Mountain Pass,") and the water was 300 ft below eye level (Zimmerman, "California Metal Mine Regains Luster). There were millions of gallons of water at the bottom (Zimmerman).

2011.[174] Yet production increased rapidly, projected to 20,000 tons by September 2012 and 40,000 tons by mid-2013,[175] out of a 2011 world consumption of about 130,000 tons.[176]

Underground mines seem to operate on roughly the same timescales of about two years. Exploring the Exodus mine in Nevada took nine months; much ore was produced during the next two years.[177] Sinking a shaft is quick, and then production can start. While permits may take time to get today, the regulatory requirements are presumably greatly reduced in war.[178] Perhaps the longest lead-time item is to precisely locate the deposits, requiring extensive exploration.[179]

With adequate manpower resources, decreased regulatory burdens and sufficient will, raw material production could be raised in several years. Mines are relatively invulnerable to conventional attack, because there is inherently little to no damage in a pit. The value at an open pit mine is the manpower and the machinery, the latter of which is quite hardy, possibly requiring a very near miss or a hit to destroy.[180] Attack on dispersed machines would be uneconomical and would require real-time intelligence on the machine location. Rail tracks in open-pit mines are relatively cheap, and quick to repair. Miners would be potentially vulnerable to an explosion in the pit. If possible targets for a missile can be identified while the missile is still in midcourse, miners could be protected. If the missile's target can only be identified in terminal phase, then it might be necessary to build temporary personal shelters inside the mine. A high foxhole density combined with the low starting manpower density might protect manpower.[182] Sustained missile attack on mines may cause casualties, but only at very unfavorable cost exchange ratios.

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[174] See Wiens, "A Visit to the Only American Mine."

[175] See Lamar, "Molycorp Says More Than 75 percent Of Phase 1 Production At Mountain Pass Committed."

[176] See "Rare Earths," *USGS*.

[177] See "Exodus."

[178] Decreased regulatory burdens may decrease mining time, possibly at the expense of the environment and of human life. Not to be callous, but starting and feeding the war economy is not cheap.

[179] See "Butte Highlands – The Next Great Mine in Montana?"

[180] See "Hycroft Mine."

[182] Molycorp plans a maximum of 200 people for both the Mountain Pass mine and the refinery. See Wiens, "A Visit to the Only American Mine."

Hard kills on the deep tunnels of underground mines are seemingly impossible, as mines are designed to handle natural tremors and stresses. However, a mine might be rendered unusable by attacking its access points. An attack on a vertical mineshaft may only cause severe damage to the upper part of the mineshaft. Building many branch backup escape shafts may be viable, combined with reinforcing the upper sides of the main shaft. Redundancy of onsite equipment might make it possible to repair the damage relatively quickly. Since instant repairs may be impossible, it would be necessary to have sufficient provisions stored below ground. Multiply redundant ventilation shafts shielded by many decoys could assure sufficient air supplies.

After mining, the next step in the value chain is the refinery. A fully comprehensive report would consider all refining processes to determine capabilities for capacity expansion as well as protection. This study only examines a few materials, starting with aluminum. Bauxite is converted through the Bayer process to alumina,[183] which is converted through the Hall process to aluminum metal.[184] Alcoa was able to build all of these 20 plants in 3 years in World War II; production multiplied more than five times within five years.[185] Since the Hall process demands much electricity, power production expansion is essential for aluminum production expansion.

This World War II production expansion case is highly relevant for aluminum. The processes have remained highly static. For many other materials these same patterns may hold, and the successes of World War II indicate high potential for quick production expansion. While knowledge lost since World War II may be a challenge, learning to use new materials is not impossible. Lockheed learned how to use titanium, which was strong enough and saved weight, for the Blackbird. It took time and money to develop knowledge about titanium – for instance, that it was incompatible with chlorine or cadmium.[186] Still, learning was relatively quick. For speed, it may be advisable to distill practical knowledge of past refinery workers as a bulwark, and further research on potential knowledge gaps is merited.

In two major areas, refining today is entirely different from refining during World War II. The first major area is rare earth minerals, and the second is composites. Rare earth mining capacity

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[183] See “Bayer Process Chemistry.”

[184] See “The Hall Process,” *American Chemical Society*.

[185] See “Alcoa’s 125 Years.” Alcoa cites that in 1944 over 800,000 short tons of aluminum were produced, while only 600,000 short tons were sold. This is a large amount of overproduction.

[186] See Rich, *Skunk Works*, 213.

expansion has been rapid. Despite massive environmental issues,[187] the Lynas plant in Malaysia[188] was built in about two years.[189]

Composite manufacturing capability has grown rapidly; seemingly keeping pace with the Boeing 787, which used large amounts of composites. Quickstep, a composites manufacturer, secured funding for its F-35 parts factory in April 2011.[190] The factory opened in June 2012,[191] and is expected to be in full operation by the end of 2012.[192]

How does refining capacity stand up to the threat of wartime attacks? For most industries, World War II can be a proxy here. Attacks on the Gebruder Giulini GmbH aluminum refinery were partially successful.[193] Direct heavy bomb hits caused shutdowns for four weeks at a time. It is unclear how much of this was due to damage to the kilns and machinery, however, as opposed to the most vulnerable parts of the plant – transformer stations and water pumping stations.[194] Only one kiln was destroyed in a raid that caused ten bomb hits on buildings.

Then, ability to damage such refining capability by ICBM attack would be limited. Electric cables, water pumping stations and transformers are far easier to attack in a conventional bombing raid than by conventional missiles. The less vulnerable kilns might be protected by underground burial and emplacement,[195] or dispersal.

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[187] See Gooch and Bradsher, "Challenges To Prospects For a Plant In Malaysia."

[188] Australia has high construction costs and powerful environmentalists. Bradsher, "Taking a Risk for Rare Earths."

[189] Began in 4/2010, with first use mid-2011 ("Lynas Rare Earths Project Update,") first phase completed in 6/2012 ("Lynas Advanced Materials Plant") and completion goal early 2013 (Bradsher, "Taking a Risk for Rare Earths.")

[190] See Falson, "Quickstep Secures $17.3m."

[191] See Falson, "Quickstep Bankstown facility to begin composites production in Q4."

[192] See "Composites Manufacturing," *Quickstep*.

[193] See *USSBS Gebruder Giulini*.

[194] Coal stockpiles also were vulnerable (represented a high carrying cost) as they were vulnerable to incendiaries.

[195] Instead of burying a refinery, it may make sense to collocate the refinery with the deposit to conserve energy.

A rare earth refinery is presumably far more valuable than a bauxite refinery. Burial may not be possible, if it is possible to penetrate the protections through repeated missile attacks, given the value of the target. Dispersal, it seems, would be possible.[196]

The next important refining process is steelmaking. In the first step, iron ore is placed in a blast furnace.[197] Capacity expansion for blast furnaces may have never happened on a huge scale in this country: In World War II, mills that were idled during the Depression were used.[198] As a timing study, Bethlehem's Burns Harbor plant took four years from groundbreaking to capacity; by parallelizing tasks and with sufficient urgency this could be cut to two years.[199] Qatar is scheduled to open a new blast furnace plant in Algeria in four years, including setup of utilities.[200] Then, it seems like blast furnaces could be expanded.

Similarly, blast furnaces can be protected. Japanese blast furnaces were very difficult to attack by aerial bombardment.[201] USSBS named the coking ovens and intra-plant utilities as the parts of the plant most vulnerable to attack. These may be highly dispersed to protect against small numbers of munitions, since an oven is composed of a sequence of cells. The furnaces themselves, however, were damaged by naval bombardment; repair would have taken about six months. This suggests that furnaces are difficult to destroy, but also difficult to repair.

Burial of blast furnaces may be possible, as might dispersion to help both expansion and protection. Mao tried dispersion to advance (b) (5) steel production in 1958.[202] Small blast furnaces were quickly fabricated, distributed and set up in backyards. The program was an abject failure. Since there was an insufficient supply of quality ore, people fed the furnaces their farm tools, causing a famine. Since coke supply was insufficient, the steel had to be remade. Lack of basic metallurgical knowledge caused many errors; still, production of some regions increased.

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[196] For instance, the many buildings at Mountain Pass could be moved apart, with value dispersed between them.

[197] See Ohashi, "Modern Steelmaking."

[198] See Herman, *Freedom's Forge*, 85.

[199] See Meyer, "The Modern History of Burns Harbor Steel."

[200] See Tuttle, "Industries Qatar Plans to Invest in New Steel Plant in Algeria."

[201] *Coal and Metals in Japan's Wartime Economy*

[202] See Salisbury, *The New Emperors*, 149-151.

This validates the basic concept of dispersion in the steel industry. Too much dispersion risks over-dilution of crucial skills, but education about basic metallurgy should enable some level of dispersion. Dispersing one plant to tens if not hundreds of sites could be a viable idea.

Next, the steel may be rolled into a sheet.[203] Rolling plants can be built quickly: Less than two years non-utility work was required for the Youngstown plant.[204] The vulnerability of rolling plants is unclear; less Japanese steel was rolled by the end of the war, but this may have been due to shifted demand, not physical damage.[205] They might be made mobile, buried, or dispersed.[206]

After steel is rolled, it must be pressed and forged. Lean production has greatly advanced pressing and forging. In the auto industry, a die tended to take the longest to switch as the line transitioned from one good to another, driving the large EOQ.[207] For pull to be economical, EOQ needed to be minimized to the target metric of SMED, single[-digit] minute exchange of dies.[208] Besides possibly making it cheaper to obtain new dies and easier for the die industry to expand, vulnerability to attack is reduced. Increased utility and mobility of dies may better permit dispersion. Even if most of the assembly line cannot be made mobile, mobility on a lesser scale might be useful here. If key parts can be safely moved in such short time periods, then it might be possible to protect these parts in a prepared revetment on warning of a missile attack.

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[203] Depending on the application, this may be a waste of overprocessing, if the next step in the process does not require the steel to be rolled.

[204] See Samavati, “Youngstown Area to Get 350 More Jobs.”

[205] See USSBS, *Coals and Metals in Japan’s Wartime Economy*.

[206] A new technology known as Castrip, which shrinks plant size by two orders of magnitude, may reduce the size to enable mobility or dispersion. See “Welcome to Castrip LLC.”

[207] Mass production tried to reduce the number of switches, leading to production according to pushed forecasts.

[208] See Womack, *Lean Thinking*, 352.

Next, it is important to consider energy. Consumption is likely to increase with economic activity. Production of energy may come under attack at various nodes, and Middle Eastern oil may be disrupted. However, the demand may be constrained in wartime. About 40 percent of American oil use is automobile gasoline, which could be curtailed in wartime.[226] The citizen will have less free time, and the government as in World War II may promote gas efficiency through carpooling, using public transportation, and curtailing speeding.[227] Likewise, civilian air travel - about 6 percent of total American oil consumption – will suffer natural cuts, complemented by

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[226] See "How the US Uses Oil" and Komanoff, "Ending The Oil Age."

[227] See "1940-1949 War Speed Limit."

increased utilization of long-distance rail and bus transportation. The 10 percent of oil used for heating may be replaced by coal and natural gas. Despite likely increases in freight oil, plastics manufacturing oil, and military and shipping consumption (combined 26 percent today), overall crude demand seems likely to decrease, and even more so refinery demand as gas consumption is cut.

On the supply side, imported oil is only 45 percent of consumption today.[228] More than a third of this comes from Canada and Mexico, and 15 percent of this comes from friendly countries in the Western Hemisphere and Europe. Only about a quarter of American production comes from potentially unfriendly countries,[229] expansion need only be limited. Installation of new derricks or wells for oil or natural gas in known fields is quick,[230] and invulnerable to conventional ICBM attack due to the large number of wells.[231] Transportation is also relatively invulnerable.[232]

Increasing refinery capacity is also relatively quick. It took only about three years to more than double the Port Arthur, TX refinery's capacity.[233] Refineries are difficult to attack: The heavy attacks on German refineries were only successful when repeated many times.[234]

Thus, the United States[235] can be relatively assured of sufficient oil supplies. The picture for natural gas, which today represents about 25 percent of US energy consumption,[236] is just as rosy.

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[228] See "How Dependent is the United States on Foreign Oil?"

[229] The 10 percent of offshore-based production may also be vulnerable.

[230] See "Oil or Gas Drilling/Development."

[231] See Kim, "Oil and Gas Map of Texas."

[232] Pipelines are presumably relatively easy to repair. Ports' weakness is limited.

[233] See "Port Arthur Expansion."

[234] See *USSBS ETO* Summary pg. 9.

[235] The Allied bloc may have severe problems. The US may need to further cut consumption to supply oil to Allies.

[236] See "Annual Energy Outlook 2012," pg. 76.

Even today, with vast untapped reserves, there is very little reliance on imports.[237] The largest vulnerability is the point where the gas is burned for power, similar in many ways to coal.[238]

Coal-based energy, 21 percent of US consumption, is first mined. These operations can be expanded and protected as discussed above. Foreign disruptions will have low impact, as today the United States is a net coal exporter.[239] The plant is the primary point of vulnerability. It has several basic stages, which may be concentrated in the same plant.[240] The furnace stage may be dispersed with smaller, even mobile furnaces, much as Mao's blast furnaces. The capability to repair or protect heating furnaces should be studied, since they may be difficult to make.

Next, the turbine converts the heat into rotational kinetic energy, much like a jet engine turbine.[241] Small turbines may be dispersed, or rapidly produced if large turbines become unusable due to attack. The generator then converts rotational energy into electricity. While making more large generators may be very difficult, civilian power consumption may also be reduced. While it may be difficult to protect large generators except perhaps by burial, small, dispersed backup generators in sequence may be useful for resilient power generation. Lastly, transformers convert electricity to cheaply-transmissible high-voltage lines.[242] Rather than raising the voltage through one large transformer, raising the voltage by a sequence of smaller, dispersible transformers may be feasible. Thus, the vulnerability of a fossil fuels plant is limited.

It is also important to consider other sources of energy. Nuclear plants, about 10 percent of current electricity generation, are potentially extremely vulnerable to attacks that are not deterred by the shield of nuclear escalation.[243] This may represent needed capacity expansion for fossil fuels and renewables in mobilization contingencies. Hydroelectric plants, about 3 percent of current generation, are also vulnerable. While dams are hard targets,[244] past attacks have

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[237] See "Summary of Natural Gas Supply and Disposition in the United States, 2007-2012."

[238] See "Electric Generation Using Natural Gas."

[239] See Watson, "U.S. Coal Supply and Demand."

[240] See "Coal-Fired Power Plant."

[241] See Eder, "GE Factory Turns Airplane Engines into Gas Turbines."

[242] This is a form of overprocessing, since the electricity is raised in voltage only to be lowered later. A solution to this is to locate new factories close to their power plants.

[243] Small, dispersable nuclear plants are being developed. See Vidal, "Mini Nuclear Plants."

[244] The Three Gorges Dam is 120 ft across at the top and 330 at the base.

succeeded,[245] and enough missiles could destroy any dam. Still, the primary damage would be flooding, to which (b) is far more vulnerable. These attacks should thus be of primary concern to (b) (5) The small contributions of other power sources are less vulnerable because they are dispersed; still, surge capacity to cover shortfalls in other energy sources should be considered.

Mobility Platforms, Weapons, and Transportation Capacity

In the mobility industry, there is cause for optimism about capacity expansion. Demand for railcars might be high, yet setup for a new factory for locomotives only took 18 months.[246] The multiple unit railcar is one area of technological exploration. Instead of a locomotive, each car has its own engine, so cars can move alone or in small groups, preventing batches.

Another crucial good is the crane. Cranes are extremely useful in shipbuilding and in shipping. One of the likely targets for a shipyard attack is the cranes, since cranes represent a high value density. Cranes on board container ships also enable use of primitive ports. Yet expansion seems possible: The Manitowoc Corporation opened up a plant in Brazil in about a year.[247] Assembly of key parts may be relatively small, so might be dispersed or made mobile.

Since a large unit necessarily takes much space to assemble, the only plausible protection solutions are burial and low cost density. Most of the floor value in an assembly plant is in the people, and in a few key machines that can be put into revetments in times of need as long as there is sufficient warning time. Indeed, assembly may even be the easiest and least-complicated step, both to expand and to protect. Toyota's Georgetown plant took about two years to the first production car after groundbreaking,[248] the Toyota San Antonio plant took about three years,[249] and the Toyota Princeton plant took about two years to set up.[250]

Many trucks, then, could be made in a protected fashion. Crucially, assembly is assembly, for trucks as well as tanks as well as aircraft; that is, assembly expansion would also be possible for these other goods. Surely, tank design has far differentiated from truck design since World War

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[245] The Möhne Dam, which was 112 ft at the bottom and 25 ft at the top, was destroyed by quite a margin (see "The Dambusters," "The Dambusters Raid 16/17 May, 1943).

[246] See "GE to Open New Locomotive Manufacturing Facility."

[247] See "Manitowoc Opens First Latin American Crane Factory."

[248] See "TMMK: Our Story."

[249] See "Toyota Starts Production at San Antonio Assembly Plant."

[250] See "Toyota Motor Manufacturing Indiana, Inc. (TMMI)" and Brennan, "Princeton: Toyota Marks 10 Years."

II, and there may be parts bottlenecks, which might be resolved by the strategy known as design for manufacturability.

The goal of wartime design is not to build something that will last for 50 years in a wide range of possible combat environments, but something that will last for five years in a better known combat environment. Still, some degree of effectiveness may need to be sacrificed to allow quantity production. The Liberty ship engine was obsolescent and a “relic,” but easy to build.[251] Even though diesel engines were less vulnerable, it was only possible to produce gas engines. While this compromised effectiveness, it made production of tanks in far larger numbers possible. It may be useful to have some high-end units to deal with similar units of the enemy interspersed with units producible in great numbers.

While design capability tradeoff is undesirable, it is attainable. However, for most key parts, expansion and protection should be possible. For airplanes, consider that it took Boeing about a year-and-a-half to open its South Carolina facility.[252] Even for complex jet engines, it seems that lean production’s flexible manufacturing is relatively quick to set up even here.[253] A large part of this effort is complying with regulations, including passing the “fan blade-off” test.[254] While guarding against these extremely rare occurrences, even if at high cost, makes sense in peacetime, wartime demand may preclude this.

Protection of airframe and aero-engine plants might leverage the large number of buildings that are needed to contain such a facility. These buildings are grouped relatively closely at the GE Lynn plant, but they could be protected or separated to require a direct hit on each building. For final assembly here and in other industries, revetment, burial, and mobility are all viable. Pratt & Whitney’s new high-concentration engine production cell reduced the space for turbine grinding almost by a factor of three, small enough to fit onboard a C-5.[255]

Some military aircraft, such as cargo planes, tankers, and B-52s likely follow the same rules as civilian airplanes. Design simplicity and reliance on electronic capability may provide a fallback solution for all types of aircraft. Still, even stealthy designs might be assembled in largely the

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[251] Herman, *Freedom’s Forge*, 181.

[252] See “Boeing Breaks Ground On South Carolina Plant” and O’Connor, “Boeing Factory Opens in S.C.”

[253] See Womack, *Lean Thinking*, ch. 8.

[254] See Norris, “Trent 1000 ready to fly…”

[255] Womack, *Lean Thinking*, 179. The cell went from 6430 ft^2 to 2480 ft^2; the C-5 has about 2299 ft^2 (“C-5 Galaxy.”)

same ways, in accordance with the general principle that "assembly is assembly." The Skunk Works adapted to working with stealth by simply lowing their error tolerances.[256]

In shipbuilding, the lessons of World War II are applicable. A ship is still a ship: The value is in weapons and electronics, not the hull;[257] a Liberty ship or Victory ship hull and engine would be adequate. The Kaiser model of World War II could work equally well today, from scratch to ships in about a year.[258] To protect a merchant shipyard with ships on the slipway, it may be necessary to rely on the hardness of the targets: Damage to a ship in a slipway might be repaired since the ship cannot sink. Shipyard infrastructure, such as gantry cranes, is mobile.

For most military ships, the same ideas as Kaiser's escort carriers are usable. The weapons are far more important than the hull: A unit with powerful electronics and ample vertical launching system (VLS) tubes may be an adequate surface combatant. Aircraft carriers and submarines are the exceptions: Both are vulnerable to attacks while under construction. Short of solutions like mobile construction docks, an alternate force structure could use converted smaller, conventionally-powered carriers with short take-off, vertical landing (STOVL) jets to fill the force. While submarine construction may be shielded as part of the nuclear deterrence, it may be necessary to use lower-end submarines.

It is crucial to consider weapons construction. Ordnance is itself mostly reliant on the chemical industry, assembly, and the semiconductor industry. The ordnance factory itself is relatively small, at least in manpower terms.[259] It may be possible to use lower-end weapons, like late World War II torpedoes, instead of advanced weapons like ADCAP for many purposes.

Semiconductor plants are difficult and expensive to build, become obsolete quickly, and are very susceptible to damage. Chips are made in a "cleanroom," with very low tolerances for particles. A minor fire and mud from firefighters' boots took down a Philips cleanroom for months in 2000.[260] It seems difficult to implement lean since the machines are truly monuments, with all of the negative impacts that this has on flow. The process is often iterative, with chips revisiting a

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[256] See Rich, *Skunk Works*, 69.

[257] Excepting niche applications like the JHSV and LCAC. The last major discontinuity was during World War II, when Kaiser's revolution introduced welding and modularity. Some changes might be needed to enable containerization.

[258] Richmond, a literal swamp at the end of 1940, had the first keel laid in April 1941 (136) and the first commissioning before 1942. (Herman, *Freedom's Forge*, 124, 136, 180).

[259] Only 250 people work at the Tucson Raytheon Tomahawk plant (Wichner, "Tucson-based Raytheon Unit…")

[260] See Sheffi, *The Resilient Enterprise*, 3-10.

machine dozens of times and ruining visual control. The operations performed on the chips are so expensive as to make it uneconomical to act on anything more than a large batch.

While expansion may be possible, protection would be more challenging. Given the high fragility and value of a semiconductor fab, the only potential strategies are burial, dispersal and mobility. However, a fab has such high value that a large number of missiles could efficiently destroy its bunker. Dispersion is impossible, since the atmosphere needs to be clean and iterations are required. Mobility is also impossible due to the large size of the fab.[261]

There are several downsides to stockpiling semiconductors before the conflict. First, producing many years of semiconductors into stockpile is a clear warning sign to the adversary. Second, it also requires both long warning times that a conflict is coming, and large disruption to civilian markets ahead of the contingency. Third, stockpiling closes the window to possibilities of technological change. It may be better to simplify the process. The process is so complex in peacetime because consumers demand large increases on transistors on a chip for graphics-intense applications. Demand in wartime may be different; computers from previous decades have solved many military computing problems such as fly-by-wire in the early 1980s.[262] Investments in a smaller, more defensible process may be more valuable than performance increases in case of mobilization. Finally, civilian software production capabilities have great potential for rapid conversion to military goods, especially given recent developments toward language commonality. As long as the US information technology (IT) industry continues to thrive, there seems to be ample capability here.

The next crucial concern is infrastructure, including roads, rail networks, ports and utility networks. Besides certain key nodes, these are relatively invulnerable to missiles. Attacks on rail and road networks did prevent German reinforcements from arriving at the Normandy beachheads the morning of 6 June 1944,[263] but this only shows that high density attacks can be successful in the short term. A road or a rail is a hard target that can be easily repaired; a much easier way to destroy a network is to destroy key bridges. The North American rail network could be cut in two by destruction of about 15 key rail bridges, each long and difficult to replace.[264]

The United States might have several defensive responses to this. First, rails might be routed over sufficiently strong road bridges, but since all bridges are potentially vulnerable this can only buy time. A second approach would use vehicle tunnels, but these are extremely expensive to

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[261] Shipborne placement seems impossible since the fabs are highly vulnerable to vibration. See Jelinek, "IHS iSuppli Issues Updates" and Hara, "Aftershocks from Japan Earthquake."

[262] See Rich, *Skunk Works*, 30.

[263] See, for instance, *The Impact of Allied Air Interdiction on German Strategy*.

[264] See Appendix Two of this report.

construct and might be profitably destroyed by a large number of missiles.[265] While re-routing transportation grids over the bridgeless desert may be feasible, it would take very long to build.

More practical would be to build rail or road bridges over dams, like the old US Route 93 on the Hoover Dam.[266] This deters attack, since damage caused to the road network would be far less than the flooding damage in (b) by reciprocal US attacks against large (b) (5) dams. Depending on the density of US dams, this could work, but it does raise ethical questions: The infrastructure is shielded against the possibility of massive (b) (5) civilian deaths.

Pontoon bridges avoid these issues, and can be strung up quickly for low price.[267] However, they have limitations, including weight capacity and water conditions, and hampers river traffic. The necessary entrance ramps might be vulnerable or expensive, and they are not even feasible in case of deep gorges.

Still, there are tools that can protect road and rail infrastructure. Ports may be vulnerable, but are potentially difficult to attack. While rail and road grids have a few key nodes that are susceptible to damage, a port's biggest vulnerability may be its cranes, which may be protected by dispersion and mobility.

Utility attack, very feasible with many inaccurate bombs, is difficult with small numbers of more expensive munitions, since utilities have low value density. One possible attack mode might be with graphite bombs, as against Iraq. A response might involve protecting crucial areas like distribution plants and creating rapid response teams that can respond to any electricity contingency. Thus, the vulnerabilities of the utility system are not paralyzing.

It is important to analyze the system's vulnerability to cyberattack. A grid is extremely vulnerable, as failures cannot be isolated.[268] However, today's grid may be overly networked: It might be possible to isolate factory networks. Pull only inherently needs a small amount of bandwidth, so reasonable precautions could limit the exposure to the cyber threat.

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[265] The Big Dig cost $15 billion just for the tunnel (Moskowitz, "True Cost of Big Dig Exceeds $24 Billion.") Much of this is likely regulation, the need to last a long time, and utilities, but the point about expenses stands.

[266] See "Hoover Dam Bypass."

[267] See Pitts, "Crossing the Rhine River."

[268] For instance, see the 2003 Northeast blackout.

MANPOWER CAPACITY

Finally, manpower is the crucial and most difficult bottleneck blocking production expansion. A levée en masse to raise warm bodies would be very feasible, but raising a skilled workforce needed to operate lean plants would be far more difficult.

The first manpower source is from the un- and underemployed. In World War II, there was high unemployment residual from the Great Depression, but even today's unemployment rate is far less than that during the Depression.[269] Today's rate will likely decrease cyclically.

Non-participants in the labor force are another source for manpower. There was much room to expand the work force in World War II, from non-participating women;[270] today labor force participation rates for working-age men and women are near 90 percent and 75 percent respectively.[271] Temporary levies on non-participants and retirees may provide room for expansion, but lack of job skills for many residual unemployed or labor force non-participants may pose a challenge.

Cuts to other sectors of the economy could vastly increase sheer manpower in both the military and the labor force. Many items produced today in the United States are luxuries in wartime: While necessary for today's standard of living, in a major war they are second to successful prosecution of the war. It is possible to re-employ people from these fields.[272] Some of 2020's projected 5 million salespeople might be spared by shifting responsibility to the customers. Likewise, the 1.6 million wholesale and manufacturing sales representatives and the 300,000 telemarketers may be re-assignable, accompanied by proportional decreases in the 1.7 million supervisors. The 2.5 million customer service representatives may be reduced at inconvenience but not at damage.

Automated machines may replace the luxury of 3.6 million projected human cashiers. In many cases, it is a luxury to be served by one of the 2.5 million waiters or waitresses instead of in a self-serve cafeteria. The 1.5 million maids and housekeepers, 1.4 million landscapers, and 1.4 million personal care aides (as opposed to retirement homes) are also a luxury.

Regulatory simplifications may also provide a labor pool. The Bureau of Labor Statistics (BLS) projects 2.1 million "bookkeeping, accounting, and auditing clerks," and 1.4 million accountants

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[269] See Smiley, "Great Depression:" unemployment in 1940 was 15 percent. This does not account for underemployment.

[270] See Goldin, "The Quiet Revolution," which lists the rate for 25-44 year old women as about 30 percent in 1940.

[271] See "Civilian Labor Force Participation Rates."

[272] For statistics, see "Occupational Operational Handbooks."

and auditors, open to a levy. Another pool stems from wartime civilian demand cuts: The auto industry, for instance, has 800,000 automotive service technicians and 180,000 auto body repairers.

However, lean manufacturing and the military demand more than "warm bodies." While mass production's very low job training requirements enabled the mass and unselective recruitment of people into factories,[273] a skilled lean team may take many years to train and integrate.[274] Even then, since lean thinking is inherently non-intuitive,[275] the extremely successful[276] lean company Wiremold, backslid to mass production under new management.[277] Besides the cultural and organizational requirements (top-level), the requirements for an individual worker are potentially onerous. Toyota estimated that only 1 percent of people were likely to "fit into the Toyota culture."[278]

It would seem that the utility of previous manufacturing experience is limited, as evidenced by the far longer job-training times. That is, the crucial characteristic of an effective lean worker is not so much technical aptitude as amenability to and understanding of lean ideas. Education as it is commonly practiced today contributes little to this understanding, as Toyota has built assembly plants even in places with extremely low educational attainment, such as Thailand, Indonesia, Kenya, and Venezuela.[279]

Lean companies look for many traits in prospective employees.[280] Some of these traits, such as motivation, are likely to be commonplace in wartime. However, other qualities, such as problem solving and ability to communicate, may be scarce regardless of the national situation. To foster these qualities in the future labor force, Toyota has turned to early education.[281] By their

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[273] See Womack, *The Machine*, 31.

[274] Womack, *Lean Thinking*, 148 claims that it may take five years to implement lean, and on 214 claim that it may take ten years to make lean sustainable, due to workforce constraints.

[275] See Ohno, *Workplace Management*, ch. 12.

[276] See Womack, *Lean Thinking*, ch. 7

[277] See Meyer, "An Inspiring Lean Tear-Jerker."

[278] See Austen, "End of the Road." Note that Toyota and lean are not synonymous.

[279] See "Worldwide Operations."

[280] See Piatkowski, "People Selection Process…"

[281] See Austen, "End of the Road."

Georgetown plant, they have helped to establish the Center for Quality People and Organizations (CQPO), which trains students to make them more amenable to lean.[282] This sort of education reform, helpful for employment in peacetime, also helps mobilization.

The other necessary factor for establishing a plant is a skilled cadre of senior managers, who take many years to train.[283] It would be even better if this cadre had understanding of defense affairs. This cadre of "sensei" can help to grow lean and plant culture like a pyramid. Since industry also has strong interests in training, there is ample possibility for collaboration between business and government for a low-cost, high-impact program.

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[282] See "Education: QUEST." The fraction of manpower not amenable to lean might be utilized in high numbers in low-automation jobs, using more primitive methods to balance shortages elsewhere in the zero-sum economy.

[283] See Shook, "What's Your Challenge?"

CONCLUSION

In past total wars, industrial nations have produced and distributed munitions based on a long-term forecast of demand. This system, inspired by contemporary ideas from the civilian market, was inherently unsatisfactory. Its model of a unitary buyer with predictable demand was unsuited to the actual phenomenon of different small military units each consuming goods at an unpredictable rate. To compensate for the ill-fitting model, these nations adopted the civilian market's concept of large stocks maintained at various points in the process. Carrying costs were high in the civilian environment, and even higher in the wartime case. As a result there was much inefficiency.

Since World War II, the competitive civilian environment has developed an extremely successful philosophy that is optimized for reducing these and other costs, inefficiencies, and wastes. In so-called "lean" production, rather than pushing pre-planned forecasts on the customer, it is better to have the flexibility to rapidly produce in response to the pull of demand by individual consumers. The flexibility that rapid and accurate responses to demand requires can be achieved only by the use of people in the capacity of problem solvers.

This study has discussed a model for responding to the wartime demands of a conflict in which there is sufficient political will for the massive dislocations that inevitably accompany mobilization, which is primarily a non-nuclear conflict, and which involves long-range precision strike against industrial facilities in both the continental United States and mainland (b) (5) In a mobilization to respond to this contingency, the premise of a unitary buyer with predictable demand is inaccurate, and induces inefficiencies and waste; the weakness of an ill-fitted model is compounded by the vulnerabilities of systems other than lean to enemy attack.

In such a contingency, a mobilization of the industrial structure according to lean principles would be better suited to the demands of the situation. Uncertainty in war is even more severe than the uncertainty in peacetime that led to a turn away from production forecasts to lean ideas. In wartime, design changes are more frequent as feedback is received from the theater. Lean production's flexibility is better able to respond to this environment

There are differences in the wartime and civilian environments that necessitate adaptations of lean production. Unlike the civilian economy, the wartime environment is zero-sum. Then, pull as implemented in the civilian free market may be complemented in wartime by principles of central management and guidance to produce an optimally efficient system. Generally, the approach of flexibility and responsiveness is superior over the approach of buffers and stockpiles; however, elements that add resilience as well as waste may be adopted in a modular form if the enemy threat demands. Thus, in this regard lean production is dominant over its predecessors.

The last crucial difference is that, in the wartime case as opposed to the civilian case, a vast increase of production of certain items is necessary. Through their flexibility, lean ideas would greatly facilitate expansion. In most sectors, most of the operations necessary to complete mobilizing could be accomplished within two to five years. The longest lead-time item would in fact be the expansion of a lean-capable workforce at all levels. Research on optimal training methods for lean production would be highly useful, and it is likely that low-cost, high-impact training programs can be developed to produce a cadre of highest-level lean operators to facilitate the expansion of production in a mobilization contingency as discussed in this study.

APPENDICES

APPENDIX ONE: ARGUMENTS AGAINST LEAN

How can the reader believe Womack and Jones, *Lean Thinking*, in their remarkable claims about lean production? At the time of their writing, they ran consulting firms dedicated to assisting lean transformations. The best way to be sure is to consider critiques of lean production.

No known sources critique *Lean Thinking*'s figures that generally firms can increase labor productivity four times over, cut delivered error by a factor of four, decrease inventory by a factor of twenty, and decrease production throughput time by a factor of twenty. Nor do sources critique *Lean Thinking*'s analysis of cases, although the work may be justly accused of mild selection bias.[284] That a company using lean production failed, however, could be due to any number of things and is no indicator of systemic problems in the face of so much success.

Nor is there much question about lean's success in the competitive market. Estimates of the prevalence of lean philosophy are between 15 percent and 60 percent.[285] No matter what the number is, corporate leaders realize that lean methods are successful and try and adopt them. In the places where an attack would be most effective, the results, lean production is relatively unscathed. Now, it is useful to consider which angles criticisms come from.

Some criticisms from the labor perspective assert that lean production has detrimental effects on labor, which is exploited and unhappy in lean plants. For example, see Graham, *On the line*, Berggren, *Alternatives to lean production*, and Rinehart, *Just another car factory?*[286]

Arguably, these criticisms can be dismissed out of hand for mobilization, where worker happiness is arguably a concern only so far as it affects material results. However, the merits of the arguments of these cases are few even in peacetime.

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[284] The case in question is Doyle Wilson Homebuilders. Womack, *Lean Thinking*, discusses the company's successful lean transformation of this company on 29-31, but the company failed in 1999 (Smith, "And In Other Business…") This company, unlike almost all others, was not mentioned in Womack's second edition follow-up. Garrison, "Residential Construction" claims that Doyle Wilson quit because lean did not catch on in his industry.

[285] See Davidson, "Lean Manufacturing Helps Companies Survive Recession." While 60 percent of companies claim to be lean, Anand Sharma, CEO of TBM Consulting, says that only 15 percent of manufacturers apply lean extensively.

[286] These and many other lean criticisms are published by ILR Press, which seems to have a very strong pro-union perspective (see "Judge William B. Groat…"). In the auto industry especially, the UAW has been unsuccessful at making headway in lean plants (see below). This may be a reason for the criticism.

The premise of Graham, *On the line*, is an infiltration of a plant to gather intelligence and talk to individual workers. This is unscientific and prone to selection bias. The reader is asked to show trust in the author, which may be difficult given the author's descriptions of her own lying.

In fact, the evidence points the other way. Proponents of lean production cite the work – unaddressed by the critics – of the positive psychologist Csikszentmihalyi, who finds that people see "activities with a clear objective, a need for intense concentration … a lack of interruptions and distractions, clear and immediate feedback… and a sense of challenge" as the most rewarding.[287] This is the environment that lean production, with its lesser division of labor, smoother workflow, and improvement exercises seeks to promote. In classical mass production, conversely, feedback, employment of skills, and interruptions may be lacking.[288]

In other theoretical lean sources, enrichment and well-treatment of the workforce takes a central role. Liker, *The Toyota Way Fieldbook* has, as one of its four tenets, "Add Value to the Organization by Developing Your People and Partners" (9). In the same source, Liker describes how "Toyota leaders are fond of saying they 'build people, not just cars.'" (265), and adds that "The Toyota Way is centered on the philosophy that people truly are the greatest asset." (265)

In mass production, the response to economic downturns is often to fire and re-hire upon better conditions.[289] Lean instead recognizes that lean workers have skills worth retaining, and rarely fire people – oftentimes making a pledge to this effect.[290] Oftentimes, workers are not fired at all in times of downturn.[291] Lean recognizes that, if increased efficiency means job losses, people will be unwilling to improve their own jobs away.[292]

Some critics claim that lean merely seeks to exploit workers and milk them for more. Surely lean seeks to allow a worker to do more; arguments that claim that this is categorically illegitimate, that a limit should be imposed on the productivity of a worker, are absurd. If the workers are happy, more productivity is most certainly not a bad thing.

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[287] Womack, *Lean Thinking*, 65.

[288] If lean is practiced as the theory demonstrates, then the theory argument should hold. Certainly, there are many cases where lean is falsely claimed to exist, and in fact there is no flow. These cases are easy to use as fodder for enemies of lean.

[289] Womack, *The Machine*, 277.

[290] Womack, *Lean Thinking*, 116, 133, 173.

[291] See Chappell, "Toyota Idles Factories…"

[292] Womack, *Lean Thinking*, 258.

Some critics also claim that lean companies exploit their workers by providing less in compensation. Any disparity that still exists is rapidly shrinking: The new UAW deal with the Big 3 drastically cuts compensation, even though the Big 3 had large layoffs and Toyota did not.[293] Despite somewhat lower pay, the workers are still happy. Despite concerted efforts and promises of better pay, the UAW has failed to unionize a single non-joint-venture transplant.[294]

Berggren, *Alternatives to lean production*, provides a more reasoned critique of lean production from a labor perspective. He argues not that lean production mistreats workers, but that Volvo's system from their Kalmar and Uddevalla plants, which used small groups to assemble entire vehicles much like craft production, was more humanistic. However, Volvo freely admitted that this system was financially uncompetitive,[295] and the year that Berggren published, Volvo announced that they were closing both plants.[296]

Other criticisms of lean production, for example Rinehart, *Just another car factory?*, can be defeated on the premise that the companies critiqued are not actually lean, or as Graban, *Lean Blog* terms it, practice "Lean As Misguidedly Executed." Rinehart's book discusses the lead-up and strike at the joint GM-Suzuki adventure, CAMI. He implicates lean production. However, it does not seem that lean production was even used at CAMI.[297] This seems to be a syndrome of the common, but incorrect, tendency to view "Japanese" and "lean" as synonyms.[298]

Another family of criticisms relies on a misrepresentation or misunderstanding of what lean production really is. Notably, the Wall Street Journal seems to publish many stories from this angle.[299] Some of these articles misunderstand that lean is about reducing staffing for the sake of reducing staffing.[300] Many more, however, concern the just-in-time element of lean production.

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[293] See Vlasic, "G.M.'s Wage-Cutting…"

[294] See Bunkley, "U.A.W. Chief…"

[295] See Prokesch, "Kinder, Gentler Plant A Failure."

[296] See "Shutdown: Swedish Carmaker…"

[297] See Chacon, "Case Study…" On pg. 9.161, the authors claim: "By the start of production in 1989, the Suzuki Production System began to deteriorate…The result was that CAMI came very close to being a traditional North American automotive plant, with few of the original benefits in place." The strike occurred in 1992.

[298] See Womack, *Lean Thinking*, 218 and 245, and Womack, *The Machine*, 242-243.

[299] See Graban, "Record of Annual WSJ JIT/Lean Blunders" for far more detail.

[300] See Graban, "WSJ Blows It On Lean."

When a company reduces inventories and is burned, there may be criticism of lean production. However, the right amount of inventory is a risk calculation; just because a company is burned does not mean that the system has failed. Often, the particular company has erred.[301] Lean proponents freely acknowledge that transoceanic shipment requires larger inventories than truck delivery, even suggesting that "oceans and leanness are usually incompatible,"[302] and arguing for emergency stocks to deal with natural disasters.[303]

Similarly, some arguments against lean production use the supply chain failures resulting from the crises in Japan and Thailand. These are addressed in Appendix Seven of this study.

Some might argue that lean production is incompatible with various industries. This may take the form that "our tolerances are too tight to permit lean," "lives depend on our industry," or a multitude of other forms. However, lean production has been successful in fields from stretch-wrap machines to wire management systems to jet engines to, of course, cars.[304] Plants that have adopted lean have been union, non-union, privately held, publicly traded, and so on. It is not impossible that there are certain industries in which lean production does not work. Given the vast array of industries in which it does,[305] however, this is unlikely.

Finally, some might argue that lean production is incompatible with some cultures. This argument used to be common, when some ill-informed Americans thought that it was inherently Japanese.[306] Due to successful transplant companies, lean American firms, and lean factories in many countries, this argument is far weaker than it once was.

A weaker version of this argument may be correct. National culture may make a difference in productivity. Womack, *Lean Thinking*, (282-284) argues that American (overcoming corporate individualism to better cooperate), German (over-division of labor), and Japanese (under-specialization) firms face asymmetric challenges. One of these systems, around the margins, simply might be better at lean manufacturing. For instance, a Toyota executive went on the record saying that he will "fear…the Germans, if they ever learn how to talk to each other."[307]

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[301] See Graban, "This Year's WSJ 'JIT'-Bashing Article, Again Misguided."

[302] Womack, *Lean Thinking*, 245-246.

[303] See Womack, "Just in Time, Just in Case, and Just Plain Wrong."

[304] Womack, *Lean Thinking*, chs. 6, 7, 8, and 10, respectively.

[305] See Davidson, "Lean Manufacturing Helps Companies Survive Recession."

[306] Womack, *The Machine*, 9.

[307] Womack, *Lean Thinking*, 215.

It is a critical question for future study whether (b) (5) culture and (b) (5) concepts of “face” impair lean production in (b) (5) It is also crucial to consider manager qualities and culture, besides the qualities and culture of floor workers, as this may explain success of transplant firms in some locations.

APPENDIX TWO: KEY BRIDGES

(b) (5) [redacted]

[redacted]

[redacted]

[redacted]

[redacted]

APPENDIX THREE: MOBILIZATION DEVELOPMENTS SINCE WWII

How have mobilization systems performed since World War II?

It is important to note that industrial innovations were made during World War II. One important innovation was statistical process control. Another was the Training Within Industry program.[308] This program helped train millions of workers without experience to make complex industrial goods, and trained workers to think instead of only using their hands. It also developed the idea of continuous improvement.[309] While it was mostly forgotten in the United States, Japan still uses TWI exercises almost verbatim. Today, TWI is resurging in the United States.[310]

In Korea, mobilization suffered the same flaws as in World War II. Industry was late to fully mobilize for the war and, even when it did, lead times were extremely long, on the order of well over a year.[311] The forces were plagued by ammunition shortages, leading to ammunition quotas that were so low as to be of widespread concern.[312] Nor was the ammunition high quality; there were recurrent problems with duds. A full 50-60 percent of illuminating shells were duds.[313] It was necessary to ship twice as many shells. While shipping was less expensive, capacity that was used for carrying dud ammunition could have instead been used for more effective supplies.

The degree of industrial mobilization in Korea, while limited, was still far more than the degree of mobilization for later conflicts, including Vietnam, the Gulf War, Afghanistan and Iraq. In cases, military lines have been rapidly configured, such as to build bunker busters for the Gulf War, MRAPs for Iraq, drones for the war on terrorism. However, this is a far different dynamic from a nationwide production mobilization for another massive-scale war.

However, recent military campaigns demonstrate the push dynamic in the supply chain is still present. Limited combat presence still leaves a heavy footprint. In Iraq in February 2009, the

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[308] See *Management and Skilled Supervision.*

[309] See Jusko, "Training Within Industry."

[310] See Jusko, "Training With Industry" and Jusko, "Introducing Training Within Industry."

[311] See Gough, *Mobilization and Logistics in the Korean War*, 58. Although this seems unbelievable, if a coke can requires nearly a year's lead time (see Womack, *Lean Thinking*, 38-43), it's conceivable to see why a tank could require 18-24 months. Perhaps some of this time refers to getting the production line moving. It was necessary to draw on the stockpiles, which were very large (see Coakley, "Highlights of Mobilization, Korean War.")

[312] See Gough, *Mobilization and Logistics in the Korean War*, 58.

[313] See Appleman, *US Army in the Korean War*, 115.

Army/Air Force Exchange Service inventoried 2.7 million candy bars.[314] Ideas of pull are still lacking compared to push.[315]

New technology and organization can solve some of the specific problems that occurred during World War II. One such idea is containerization. World War II's jumbled, wasteful mess was a natural consequence of entropy-inducing manual operations such as repeated loading and unloading as well as lack of cataloguing. World War II saw one way to mitigate these problems – palletization, or stacking items on pallets rather than handling them individually. However, it was not widely adopted.[316] After the war, the idea of shipping in large pallets, or containers, arose.

The military was a relatively early adopter of container technology; problems in Vietnam were greatly eased by use of container technology.[317] However, it seems as if these logistical ideas have stayed largely contained in the one small step of trans-shipment, and the entire chain between factory production and distribution to consumers has not been integrated.[318]

There have been recent efforts to more fully develop ideas like just-in-time in logistics contexts, such as, for instance, Velocity Management.[319] Still, even with improvements in logistics, the driver of cost and footprint is often responsiveness of the industrial base.

Military culture may contain useful lessons for an industrial expansion, as the military has evolved to adopt in large part lean ideas about the role of people and technology. The principle

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[314] See Shachtman, "Iraq Withdrawal." For a force the size of the one in Iraq, this seems like a huge stockpile.

[315] See, for instance, Burgess, "AAFES Sales Directorate," which admittedly is not strictly a military supply chain.

[316] See Dworak, *Victory's Foundation*: it worked well (pgs. 205, 273) but did not catch on (273).

[317] See Tomlinson, *History and Impact of the Intermodal Shipping Container*, and "History of Containerization," *World Shipping Council.*

[318] It's also unclear the extent to which containerization is thought of as a tool for use in contingencies. Despite the fact that 60 percent of the value of goods shipped at sea is containerized "History of Containerization," *World Shipping Council*, the Military Sealift Command has only five container ships out of 110 total ships ("Military Sealift Command.") One hopes that this is due to the large civilian container capacity that may be leveraged in wartime.

[319] This looks a lot like lean – see, for instance, Brauner, "Velocity Management," or Walden, "A Velocity Management Update." This could be a topic for further research.

“respect for people” is alive and well in the US military. The US military respects its soldiers far more so than most militaries, such as the often brutal South Korean army.[320]

Furthermore, the US military, however, recognizes a narrower divide between physical and mental labor. Junior officers are not given rigid orders, but instead given far more authority than other militaries. That is, they are encouraged to use their minds, because the military recognizes value there. This in turn leads to ideas that improve the way the military operates.[321]

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[320] See Sang-hun, “A Korean ‘Sacred Duty.’” Some may justify hazing in that harsh people can build strength, and respect is manifested by building a person who can survive better. In other words, the central goal is still to build people, just as Toyota claims to “build people, not just cars” (Liker, *The Toyota Way Fieldbook*, 265). Still, there is a point beyond which it becomes brutality.

[321] The military recognizes value in the diffusion of these ideas. The formal way, through vertical channels, may be effective depending on the personalities of the officers. To complement natural social horizontal channels, the Army has worked to open new means for horizontal diffusion, such as companycommand and platoonleader (see Dixon, *Company Command.*)

APPENDIX FOUR: PERFORMANCE OF OTHER COUNTRIES IN WORLD WAR II

Other countries were, in absolute terms, far less successful than the United States in military production during World War II. As American production was vastly disproportionate to American population, the usual and correct lesson is that the American system was far superior in terms of efficiency and output to the predecessor systems that were still used in Europe.

The British economy shows very clearly that the wartime economy is zero-sum: The British literally ran out of manpower. The British literally maxed out their manpower pools.[322] The United States had not reached the same levels.[323]

The German economy shows one method of protection against attacks. The German system, like more developed mass production, did not seem to be flexible. Then, the German economy's response to attack can serve as a proxy for a mass production system. The German economy did not warm up until 1943,[324] when Allied bombing was already problematic. The British model of firebombing cities to reduce morale was ineffective from an industrial perspective since Germany's factories were mostly out of the city centers.[325] The American model was also substantially ineffective. The Allies consistently overestimated damage and underestimated German responsiveness. The Allies continually shifted between industries, between ball bearings, aircraft, oil, U-boats, and V-weapons.

The Germans were able to continually reconstitute capacity that had been destroyed by Allied attacks,[326] in part by employing large numbers of people to respond. The idea of being able to bring rapid reinforcements to any area is perhaps worthy of emulation.

Eventually, the Germans ran out of oil, due in part to progressive damage and in part due to Soviet recapture of the Romanian oil fields.[327] Given the use of thousands of bombers every night, the American strategy was ultimately successful, although extremely suboptimal.

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[322] See, for instance, Harrison, "Resource Mobilization for World War II."

[323] Harrison, "Resource Mobilization for World War II," 19 suggests that in June 1944 40 percent of the US labor force was in the armed forces or doing war work, as opposed to 55 percent in the UK.

[324] See Pike, "Military Industry and Economic Mobilization." Full mobilization did not take place until 1944.

[325] See USSBS ETO summary report, 3-4.

[326] For instance, it was necessary to bomb the synthetic oil plant at Leuna 22 times, because it kept returning to production. See USSBS, Overall ETO report, pg. 42.

Besides simply reconstituting production, one of the German ideas was extensive burial of production facilities. Allied failure to discover the Mittelwerk plants demonstrates the difficulty of finding buried industrial sites even with many workers.[328] The Germans extensively used slave labor and prisoner-of-war labor to facilitate digging and operating these sites.[329]

The Japanese never had industry nearly as centralized as the United States. In response to early bombing raids, they began dispersal projects.[330] However, during the time period, they failed to fully reconstitute production – in other words, the dispersal project failed to be completed in the time that events had allotted.

Dispersal must have been more difficult then, than now. It would seem that a robust communications system and a high volume of communications must have been necessary to run the system. Communications were far slower before the widespread use of digital means. Otherwise, the greatly increased waiting with steps induces much efficiency. This is even truer under conditions of heavy enemy bombing, which hamper communications.

Dispersal was defeated by firebombing, which provided an effective means to destroy entire areas. Then, it was not necessary to identify and target a significant proportion of the facilities; the facilities in a certain area were all indiscriminately destroyed.

The Soviets still employed some craftsman techniques and possibly some imported Fordist techniques at transplants, but little seems to be known. During the primary period of interest about economic mobilization in World War II, Soviet files were still closed to Western researchers. Soviet process technology in World War II is then worth further study.

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[327] See, for instance, USSBS Overall ETO report, pg. 43, which has charts for oil consumption and production.

[328] The US also recognized the strength of this deception tactic; for instance in the Lockheed Burbank plant (see Frucci, "How to Disguise an Airplane Factory."

[329] See Walden, "Mittelwerk/Dora." The Germans also tried dispersal: see Brodie, *Strategy in the Missile Age*, 117.

[330] See USSBS, *Pacific Summary Report*, 16.

APPENDIX FIVE: PRE-WORLD WAR II PRODUCTION SYSTEMS

It is important to understand how military production in mobilization cases has worked. Until relatively recently, military and civilian production systems have been based off craft production. The beginning to the end of this tendency can be traced back to the Napoleonic Wars. Production was generally craft-based, made by skilled artisans; however, there were exceptions. The Portsmouth Block Mills produced pulley blocks for ships using mass-productive techniques.[331] It seems, however, that the arising industrial techniques did not become widespread.

Generally, wartime production was increased by demanding more from existing manufacturers, whose capacity was not fully used for military goods before the war.[332] Perhaps the most critical military tool was total access to national resources, both manpower and material.

The American Civil War was typical of this.[333] Added industrial production was achieved mainly by prioritization. In the South, the Tredegar Iron Works were an example of this. They were assigned a high priority, and the Confederate capital was moved to Richmond in part to be nearer to this key economic facility.[334] Before the war one of the biggest iron facilities in the entire country, Tredegar produced over half of the cannon used by the South.[335]

However, this feat of production was not very impressive compared to later production. About 1000 cannons were produced during the war, which averages to less than one cannon a day.[336] As an industrial feat, this is hardly comparable to the successes enjoyed in World War II. The limited success may have been achieved only by prioritization of slaves and coal,[337]and reallocation of flexible ironworks time from civilian production to military.[338] The production scheme of the

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[331] See Mauranen, "Portsmouth Historic Dockyard…;" "Portsmouth Block Mills," Txnologist; or Coad, *The Portsmouth Block Mills*.

[332] That is, it seems like there was an implicit reserve capability stockpile. Given how often commitment to war occurred, and how small of a slice this industrial capacity was, perhaps this was the optimal solution.

[333] As another example, in the Franco-Prussian War, Krupp merely got priority of resources, it seems.

[334] See, for instance, "Tredegar Iron Works," National Parks Service.

[335] See, for instance, "National Parks Service Programs…," National Parks Service.

[336] See "Tredegar Iron Works," National Parks Service.

[337] See DeCredico, "Richmond During the Civil War."

[338] Conversion was simple because there was no need for great precision in forging many of the smoothbores.

North was symmetric, except with more production due to the greater number of works. Commitment of resources, however, seems to have been less than total.[339]

World War I was fought on a far larger scale than the previous wars. From the American perspective, mobilization was a partial failure. Industrial mobilization failed, in the sense that goods needed in theater were not delivered there within sufficient time to affect the outcome of the war; American soldiers were armed with surplus French and British arms.

At the same time, American industrial capability was inexorably being brought to bear.[340] The GDP of the United States, circa 1900, was about as much as the combined GDP of the UK and Germany;[341] this was reflected by the extremely large target production figures.

Still, macro-economically, the United States never fully committed to the war effort. Defense spending peaked at 22 percent of GDP in FY 1919; it was 16 percent in FY 1918 and 5 percent in FY 1920.In FY 1919, 22 percent of GDP was government defense spending.[342]

There was very little time between the declaration of war and the end of hostilities for American industry’s strength to be brought to bear. Few preparations were likely made before the declaration of war in April 1917; the war ended only 19 months later. The priority of production perhaps received lower priority than it might have because of some traditional attitudes about war. The Army chief of staff, Gen. March, asked about how he planned to get troops from the French debarkation ports to the front, responded “What have they got feet for?”[343] The American focus seems to have been more on fresh manpower than on industrial goods.

Industrially, priority allocation was the most essential task. Bernard Baruch, chairman of the War Industries Board, wrote mainly about connecting the right priorities with sources of raw

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[339] According to Chantrill, “US Government Spending,” the peak rate of defense spending was in FY 1865 (Note that the fiscal year was July to June before 1976; see ”Trust Fund Operations…”), at 11.8 percent of GDP. These numbers may be problematic, because it’s unclear how the Confederacy is counted.

[340] See Baruch, vol. 2.

[341] See Dorling, “Wealth Year 1900,” with the usual caveats about inaccuracy of such measurements.

[342] Chantrill, “US Government Spending.” Note that large formations were deployed in Europe throughout FY 1919.

[343] Baruch, vol. 2, pg. 57.

materials.[344] In major industries, the problem was not to establish but to convert existing capacity, which was relatively easy given the state of technology.[345] This program was relatively simple.

The intransigence of key industrial personae, such as Henry Ford, who by refusing to shut down civilian car production misaligned the raw materials sources with the production priorities, contributed to delays. Valuable time was lost in convincing these manufacturers to support the war effort. The low impact of mass production means that there is little to be learned.

Mobilization in Europe was similar, with civilian industrial mechanisms very well adapted to military production.[346] European commitment to the war was far more total than American commitment. The British reached a peak of 47 percent of GDP as defense expenditures in 1918, barely lower than the 52 percent peak of World War II.[347] Central Powers and Entente production system innovations in wartime would make an interesting future study topic.

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[344] Baruch, vol. 2.

[345] The British, however, had to build an entirely new ammunition plant at Chilwell. See “Wartime Factory Disaster,” BBC

[346] See, for instance, “Blister Agent…”

[347] See Chantrill, “Time Series Chart of UK Public Spending.”

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[355] This page specifically references Japan: “Self-checking was a Skunk Works concept now in wide use in Japanese industry and called by them Total Quality Management.” It seems that the Japanese did come up with this concept independently of the Skunk Works, and referring to this practice as a separate name may tend to detract from the holistic view of lean philosophy, but it is interesting to note that Rich was aware of similarities between Japanese management practices and his own.

APPENDIX SIX: SKUNK WORKS

It is important to understand exactly what lean production is, and what lean production is not. Certainly, many of the elements of lean production are intuitive; that is, they are "common sense" instead of any organized production philosophy. Certainly, some of these elements arose in places not traditionally associated with lean production. While these ideas may have value individually, perhaps the biggest contribution of Toyota was to organize these scattered managerial elements into an organized and institutionalized production philosophy.

One example of independent development of many of these principles is the ubiquitous Lockheed Skunk Works. This group enjoyed spectacular success relative to its competitors during the Cold War. Upon exploration of Skunk Works management techniques, it appears that the shop was able to succeed in part because they had implemented many of the elements of lean production, if not the entire production philosophy.

In Ben Rich's book *Skunk Works*, there are numerous examples of elements of lean production, some of which are contained in the basic 14 management points laid out by founder Kelly Johnson (51-52). Johnson recognizes the value of flexibility as compared to rigidity, since he and lean proponents see uncertainty as salient in the environment. As in lean production, the project manager is delegated far more powers than in a mass production company. It is also, says Johnson, crucial to avoid the duplication of inspection. Inspections should not only be done at the end of the process, but every day. Furthermore, the Skunk Works recognized that workers could and should be trained to recognize defects, so as to prevent waste and rework (47-48,[355] 338).

While some of these points were enshrined in Skunk Works law, others became matters of routine practice. The idea of developmental concurrency was viewed as effective (332). Rich corroborates Dr. Womack's points about the need for an authoritative project manager (114, 317), and notes the extreme importance of having a trained cadre of managers (326). The engineers and designers were located very close to the shop floor, not in a different city, because Kelly Johnson recognized the value of having close communication (46, 115). Indeed, these "white-collar" workers were able to take over floor production themselves in response to labor problems (50).

This interchangeability of labor, another tenet of lean production, recurred in other places. Particularly, Rich mentions the value of hiring generalists instead of specialists (318). While lean production seeks to hire for amenability to lean ideas, not necessarily general engineers, the general concept that flexibility in labor is a better response to uncertainty than rigidity of strict labor divisions is the operative principle in both cases.

The Skunk Works developed metrics that were closer to those of lean than to those of mass. He describes how his competitors took the classical mass production view that efficient production was a function of large batch sizes, while his operation saw success as stemming from "quality training, careful inspection, supervision, and high worker motivation" (89-90).

It is clear, then, that many lean practices regarding manpower evolved in the Skunk Works. Notions of pull, however, were less developed. The Skunk Works recognized that inventories were costly. Their proposed solution was to attempt to damp the uncertainty that drove the need for inventory (325-326).[356] The importance of supplier continuity is stressed (333).[357]

In other cases, however, it is clear that no semblance of just-in-time was used. Rich talks about multi-year stockpiles (335); he notes measures to reactively mitigate the cost of stocks on the floor (77) without thinking about proactive measures. That is, there were crucial pieces of the lean production philosophy that were missing from the Skunk Works picture. It also seems that the Skunk Works lacked a coherent philosophy to collate all of these tenets.

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[356] While this concept may be feasible in this particular case, in the wartime case uncertainty may not be controllable.

[357] Here, Rich specifically mentions Japan, for what the author believes is the second and last time: "Japanese auto manufacturers discovered long ago that periodically switching suppliers and selecting new ones on the basis of lowest bidders proved to be a costly blunder." He may not understand the full reasons for this, however: he claims that new companies tend to under-bid, and there is an expense of rework that comes with the quality drop. Perhaps more important is the trust building that is desirable to sustain just-in-time.

APPENDIX SEVEN: SUPPLY CHAIN MANAGEMENT AND RISK

Why is it safe to reduce inventories in a world so filled with fog? The ultimate proof is best found in its results. The successful Toyota Takaoka plant reported an average inventory size of two hours.[358] The California GM-Toyota joint venture plant, NUMMI, reported two days of inventory, even though some parts were shipped trans-Pacific.[359]

The system has performed spectacularly in responding to unpredictable low-end, day-to-day contingencies such as late truck deliveries. It has also performed well toward the higher end of the disruption scale,[360] for instance in response to the Aisin fire.[361]

Toyota's brakes integrally included P-valves, valued at $10. Aisin Seiki Co. had come to produce 99 percent of Toyota's P-valves in their Kariya factory. On 1 February 1997, this plant was mostly destroyed in an accidental fire. Toyota's plants ran out their one-day stockpile[362] on 4 February[363] and 20 of 30 were idled.

Since repair of Kariya was expected to take months, Toyota and her supplier group had to scramble to use manufacturing facilities of other companies to make the somewhat complex P-valves. Companies from auto parts suppliers to sewing and fax machine makers like Brother Industries to engine parts manufacturers rapidly converted operations to first deliver P-valves only two days after the fire. In total, only 4.5 days of production were lost.[364] Lean's inherent flexibility, which enables response to shifting demand, seems to have been a crucial enabler.

Despite the loss of 4.5 days of production, Toyota essentially viewed this as a confirmation that their levels of stocks were correct. The low probability of recurrence of random events like this

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[358] Womack, *The Machine*, 83.

[359] Womack, *The Machine*, 83. It's unclear how many parts these transplants shipped. Womack, *The Machine*, 83 claims "almost all of the parts" were sourced in Japan, yet Klier, *Who really made your car*, claims that the vast majority of supplies for Japanese transplants were domestically sourced.

[360] The best general source on supply chain management is Sheffi, *The Resilient Enterprise*.

[361] For more on Aisin, see Sheffi, *The Resilient Enterprise*, 211-215, which this summary draws heavily on.

[362] See Nishiguchi, "The Toyota Group and the Aisin Fire," 5.

[363] In 1997, 1 February was a Saturday and 4 February was a Tuesday.

[364] Sheffi, *The Resilient Enterprise*.

one, combined with the relatively low cost of the incident due to the quick scrambling ability, was viewed as being less than the cost of carrying greater stockpiles.

A classical mass production facility would have responded differently.[366] The plants would not have felt the impact right away due to stockpiles, and would have continued producing. Mass production's emphasis on forecasts rather than flexibility, however, would have made any attempt to reconstitute production take a very long time. If, as likely, the disruption of the original supplier lasted longer than the stockpile size,[367] production would have stopped.[368]

Lean production has responded to disasters of a larger scale than Aisin. For example, a contract dispute between the users of West Coast ports and the union responsible for loading and unloading container ships resulted in a lockout from 27 September 2002 to 8 October 2002.[369]

The lockout was not without warning; in June 2002 companies began expediting shipments in preparation. Costco and Wal-Mart, using flexible lean operations, were able to pull from their Asian suppliers ahead of the disruption so that they were not shorthanded.[370] NUMMI, the GM-Toyota collaboration that used parts from Asia, only pulled shortly before the lockout. These goods were only sufficient for four days, forcing the plant to idle and use air freight.

It is unclear why NUMMI failed to anticipate the problems in the way that Costco and Wal-Mart did. Nor is it clear how a mass production plant would have responded, since the continual backlogs might have run such a plant out of stockpile. This case, then, poses more of a challenge to long ocean supply chains than to lean production.

Many sources have criticized lean production's response to catastrophic events,[371] in particular the responses to the 1995 Kobe earthquake, the 2011 Thailand floods, and the 2011 Tohoku

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[366] The open record doesn't seem to contain many examples of point failures in a long, mass-based supply chain.

[367] Aisin lost five weeks of production (Sheffi, *The Resilient Enterprise*, 214), as opposed to GM Framingham's stockpile of two weeks (Womack, *The Machine*, 81).

[368] They might have stockpiled cars produced without P-valves, necessitating costly rework, just like engineless B-29 airframes were left on the runway so as to count towards monthly totals. (Herman, *Freedom's Forge*, 308)

[369] For more details, see Sheffi, *The Resilient Enterprise*, 61-64.

[370] This is inferred from Sheffi, *The Resilient Enterprise*, 62.

[371] The open record does not seem to contain sufficient detail on mass production systems in catastrophes.

earthquake.[372] However, Toyota was fully running only a week after the Kobe earthquake,[373] and the Tohoku earthquake caused a loss of only two months of production.[374]

Smith, in “Time to Rethink JIT?,” suggests “scaling back” JIT to hold a month’s worth of inventory. However, for low-frequency events such as the Kobe earthquake, the accumulated carrying cost on that inventory, combined with obsolescence costs, would very likely add up to more than the unlikely contingency cost of the one week of lost production.

During extremely low-frequency events such as the Tohoku earthquake, it is unlikely that the extra month of stockpile could even be assembled in a time of chaos. If it could, it would not cover the shortfall in the worst plants, and the expense of maintaining the inventory everywhere would likely exceed the benefit of having some additional capability at the worst-hit plants.

Such a strategy would also only respond to a limited set of contingencies. Certainly keeping extra inventory would not have helped Honda respond to the Thailand floods, as their assembly plants were literally submerged.[375] An extremely long stockpile would have been required for Toyota to deal with the three months’[376] flood. Part of the inability to respond quickly was due to the involvement of semiconductors,[377] which are a niche component that may not follow the normal “rules” of lean production; yet, stockpiling in the case of semiconductors is likely a losing strategy due to rapid obsolescence times.

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[372] For example, see Smith, “Time to Rethink JIT?” or DeBord, “Lean Production: Another Casualty…”

[373] See Van der Putten, “Japan: One year after…,” 13.

[374] According to *Annual Report 2011* pg. 21, Toyota lost 800,000 units of production, some of which might have been regained. Toyota’s 2010 production was over 8 million (*World Motor Vehicle Production*), which indicates about a month’s production loss. But Bowman, “Toyota and Nissan…,” indicates that Japanese production was on the order of 3 million, which indicates a higher loss in Japan. Since much of the damage was caused not to assembly plants but parts plants, it is unclear which metric is more meaningful.

[375] See O’Toole, “Thailand Floods…”

[376] The floods began in October 2011 (O’Toole, “Thailand Floods…”) and ended in mid-January 2012 (“Thai Floods: Toyota to Return…”).

[377] See Woodyard, “Toyota Slows…” or Krisher, “Floods Force Honda…”

APPENDIX EIGHT: WORLD MINERAL RESERVES

This appendix is a list of the world distribution of reserves[378] of certain materials[379] in various countries. High current production likely means that reserves are high enough to permit expansion[380] to match possible increased demand.[381] If production figures are unavailable, high estimated reserves will also suffice for the purposes of this study. Unless otherwise specified, the source is USGS, 2012.[382]

- All arsenic used in the United States is imported; however, the United States has substantial arsenic reserves, like Peru, Chile, and Canada.[383]

- All asbestos used in the US is imported; however, 92 percent of these imports are from Canada.

- All bauxite used in the United States is imported, much from massive South American reserves.

- All cesium used in the United States is imported. Canada has very large cesium reserves.[384]

- All fluorspar used in the United States is imported. Mexico and South Africa hold large reserves.[385]

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[378] This is a technical term (see "Abbreviations and Units of Measures," 194.) It refers to the proportion of resources for which extraction is economically feasible at time of writing. While reserves are depleted, more deposits are discovered and the calculation for what is economically feasible to extract changes.

[379] These are the materials contained by the USGS in the "Mineral Commodities Summary."

[380] This does not yet make the case that expansion would be quick.

[381] Without accounting for changes in material demand, patterns of mineral production and consumption could be substantially different due to depletion. However, given the current robustness of the Allied material position, it is unlikely that these shifts would change the fundamental state of affairs.

[382] Rather than citing many sources, the URL is http://minerals.usgs.gov/minerals/pubs/commodity/<x>/mcs-2012-<y>.pdf, where <x> is the name of the mineral, and <y> is the first five letters of the mineral if it's longer than five letters.

[383] See http://minerals.usgs.gov/minerals/pubs/commodity/arsenic/arsenmcs05.pdf.

[384] See http://pubs.usgs.gov/of/2004/1432/2004-1432.pdf

- All natural graphite used in the United States is imported. While (b) has by far the largest reserves, huge amounts of graphite relative to yearly US consumption are found in Brazil and Mexico.[386]

- All indium used in the United States is imported. Imports from (b) stand at 31 percent (and Canada and Belgium combined at 34 percent), yet development of substitutes is underway.[387]

- All manganese used in the United States is imported. Most of these imports are from Africa, with particularly high imports from Gabon and South Africa.

- All sheet mica used in the United States is imported. India holds the biggest reserves.

- All niobium used in the United States is imported, almost all from Brazil.

- All quartz crystal used in the United States is imported. The major sources are Brazil, Germany, Madagascar, and Canada.[388]

- All rubidium used in the United States is imported. The largest import source is Canada.[389]

- All scandium used in the United States is imported. Although it is believed that most US scandium is imported from (b) (5) resources are known to exist in many countries.

- All strontium used in the United States is imported. A large majority of imports are from Mexico.

- All tantalum used in the United States is imported. Australia and Brazil hold large reserves.[390]

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[385] See http://minerals.usgs.gov/minerals/pubs/commodity/fluorspar/fluormcs07.pdf

[386] See http://minerals.usgs.gov/minerals/pubs/commodity/graphite/mcs-2012-graph.pdf. US consumption is on the order of 50 tons per year out of a world total of 925 tons per year, suggesting either that much reshoring would need to be done in a wartime contingency, or that American industries use commodities other than graphite.

[387] See http://minerals.usgs.gov/minerals/pubs/commodity/indium/mcs-2012-indiu.pdf.

[388] See http://minerals.usgs.gov/minerals/pubs/commodity/silica/quartmcs04.pdf. This report seems obsolete and vague.

[389] See http://minerals.usgs.gov/minerals/pubs/commodity/cesium/rubidmcs05.pdf.

- All thallium used in the United States is imported, almost all of which is imported from Russia and Germany. The United States has substantial reserves relative to current consumption.

- All thorium used in the United States is imported. Most thorium is imported from Western Europe and Canada, and the rest is from India.

- Almost all gallium used in the United States is imported, most from Western Europe and Canada.

- Almost all iodine used in the United States is imported, almost all from Chile.

- Almost all gemstones used in the United States are imported, nearly all from friendly countries.

- Almost all germanium used in the United States is imported, with significant reserves in Africa and Europe.[391]

- Almost all bismuth used in the United States is imported. While (b) [redacted] is by far the biggest producer and has most reserves, there are still relatively large reserves in South America. Note that uses of bismuth are limited.

- Almost all diamonds used in the United States are imported. Stones are mostly produced in Africa. While many dust bits come from (b) (5) [redacted] this is a refining function. Most diamonds used are synthetic.

- Almost all platinum used in the United States is imported. Although the United States has modest reserves, the vast majority of known reserves are in South Africa.

- Almost all antimony used in the United States is imported. Bolivia and Russia have large reserves outside (b) (5) [redacted] the United States also may have substantial reserves.

- Almost all rhenium used in the United States is imported, mostly from Chile or Kazakhstan. There are substantial US reserves.

- Almost all dimension stone used in the United States is imported, but there are large US reserves.[392]

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[390] See http://minerals.usgs.gov/minerals/pubs/commodity/niobium/mcs-2011-tanta.pdf.

[391] See http://minerals.usgs.gov/minerals/pubs/commodity/germanium/germmyb02.pdf. This is relatively more dependent on (b) [redacted]

- Most potash used in the United States is imported, almost all from Canada.

- Most vanadium used in the United States is imported. Besides (b) (5) South Africa and Russia hold large reserves.

- Most barite used in the United States is imported. India and Algeria hold large reserves outside of (b) (5) the United States also has substantial reserves.

- Most silicon carbide used in the Unites States is imported. However, this is a synthetic material, and the American resource endowment is no constraint.[393]

- Most tin used in the United States is imported, mostly from Peru and Bolivia.

- Most cobalt used in the United States is imported. The Congo and Australia hold the largest reserves.

- Most silver used in the United States is imported, the vast majority from Mexico and Canada.

- Most zinc used in the United States is imported, the vast majority from Canada, Peru, and Mexico.

- Most titanium used in the United States is imported, the vast majority from Kazakhstan and Japan. However, much titanium production is for paint, which is nonessential.

- Most peat used in the United States is imported, the vast majority from Canada.

- Most chromium used in the United States is imported. The largest reserves are held by Kazakhstan, South Africa and India.

- Most palladium used in the United States is imported. Russia is the biggest importer, followed by South Africa and Europe. This makes it one of the potentially more worrying materials.[394]

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[392] See http://minerals.usgs.gov/minerals/pubs/commodity/stone_dimension/mcs-2012-stond.pdf.

[393] See http://www.britannica.com/EBchecked/topic/544369/silicon-carbide and http://www.washingtonmills.com/products/silicon-carbide/.

[394] See http://minerals.usgs.gov/minerals/pubs/commodity/platinum/platimcs07.pdf.

- Most magnesium compounds used in the United States are imported. The biggest producers are Israel and Canada. Additionally, this process is synthetic and not based on deposits.[395]

- Much of the nickel used in the United States is imported, mostly from Canada or Russia. Large deposits are held in Brazil and New Caledonia.

- Much of the silicon used in the United States is imported, but the United States has ample silicon reserves.[396]

- Much of the fixed nitrogen and ammonia used in the United States are imported; however, since this is produced from the atmosphere, location of deposits is not a concern.[397]

- Much of the garnet used in the United States is imported. Most imports are from India or Australia, although the United States has substantial reserves.

- Some of the gold used in the United States is imported, almost all from North and South America.

- Some of the tungsten used in the United States is imported, although the United States and Canada have substantial reserves.

- Some of the copper used in the United States is imported, mostly from Chile, Canada and Peru.

- Some of the magnesium metal used in the United States is imported. Since magnesium is derived from seawater, the geography of deposits is irrelevant.[398]

- Some of the perlite used in the United States is imported, all from Greece. The United States has large reserves.

- Some of the sulfur used in the United States is imported, the vast majority from North America.

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[395] See http://minerals.usgs.gov/minerals/pubs/commodity/magnesium/mcs-2012-mgmet.pdf.

[396] See http://minerals.usgs.gov/minerals/pubs/commodity/silicon/silicmcs07.pdf.

[397] See http://minerals.usgs.gov/minerals/pubs/commodity/nitrogen/mcs-2012-nitro.pdf.

[398] See http://minerals.usgs.gov/minerals/pubs/commodity/magnesium/mcs-2012-mgmet.pdf.

- Some of the salt used in the United States is imported, mostly from Canada and Chile.

- Some of the beryllium used in the United States is imported. It is unclear what the sources of this are; the United States is listed as having the vast majority of beryllium production. Imports, mostly from Russia and Kazakhstan, may be related to refining, not deposits.

- Some of the vermiculite used in the United States is imported. The United States has very large reserves.

- Small proportions (<15 percent) of the aluminum, gypsum, phosphate rock, iron, steel, iron and steel slag, cement, pumice, industrial diamond, lime, and crushed stone used in the United States are imported.

Rare earths are the most notable set of commodities not considered; they deserve special attention. This is because they have received extensive recent media coverage as a potential source for scarcity and may be of particular interest; however, concerns are unwarranted.

In recent years, (b) [redacted] has produced a vast majority of the world's rare earth metals, up to 95 percent.[399] Yet (b) [redacted] only holds about half of the world's reserves; very substantial reserves are held by the United States and former USSR. [400] However, this imbalance is disappearing.

(b) [redacted] allegedly decided to embargo rare earth exports to Japan after the 2010 Senkaku incident.[401] (b) [redacted] continued to take risks by lowering her export quota by a third.[402] It seems to have backfired: The United States, the European Union and Japan have taken the incident to the WTO.[403] Companies are taking actions to open mines in other countries. The Mountain Pass, California mine, which formerly produced the majority of the world's rare earths, is being reopened.[404] The Australians and the Malaysians are rushing a large new project that is nearing completion. [405] New projects are advancing in Canada, [406] Nebraska, [407] Tanzania, [408] and

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[399] See Menzie, "Technical Announcement."

[400] See http://minerals.usgs.gov/minerals/pubs/commodity/rare_earths/mcs-2012-raree.pdf

[401] See Tabuchi, "Japan Calls on (b) (5) [redacted]

[402] See Yap, "(b) [redacted] Reaches Out to Its Adversaries."

[403] See "Obama announces WTO Case."

[404] See Ratnam, "Rare Earth Supplies in U.S. to Meet Defense Needs."

[405] See "Foundations for the Future." While the refinery is in Malaysia, the deposits are well-located.

Vietnam,[409] and prospecting continues in other places.[410] Some industry observers indeed predict coming surpluses.[411]

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[406] See “Thor Lake Introduction.”

[407] See White, “Quantum Rare Earth’s Dickie Outlines ‘rosy’ Future of Niobium.”

[408] See “Maiden Resource, Ngualla Rare Earth Project.”

[409] See “Vietnam Inks Rare Earth Agreement With Japan.”

[410] See http://minerals.usgs.gov/minerals/pubs/commodity/rare_earths/mcs-2012-raree.pdf.

[411] See Fickling, “Rare Earths Seen Growing Less Rare.”

APPENDIX NINE: MOBILIZATION CHART

Industry Name	Today[412]	Cap. Ex.	Protection[413]	Utility of lean[414]	Research foci	Preparatory work today
Mining	A	4 yr	Low value concentration	Unclear	Manpower or machine shortages	Mapping of deposits for quicker expansion
Refineries and processing plants	G	4 yr	Intra-plant dispersal lowers vulnerability to smart weapons (WWII case)	IEP	Composites, fineness of analysis	New plants with built-in dispersal, catalogue of lost skills
Steelmaking	G	3 yr	Intra-plant dispersal lowers vulnerability to smart weapons (WWII case)	IEP	Fineness of analysis, Maoist dispersal methods	New plants with built-in dispersal, catalogue of lost skills
Assembly	G	2 yr	B, D, R, M, depending on industry	IEP, expansion, protection, better fits wartime	Potential for conversion, revetment; machine tools	Unclear
Planes	G	2 yr	B, R; D, M for certain areas	IEP, expansion, protection, better fits wartime	Machine tools; design for manufacturability	Preservation of knowledge lost due to cuts
Ships	A	3 yr	Intra-yard dispersal, repair responsiveness	IEP, expansion, protection, better first wartime	Machine tools; design for manufacturability; protection	Unclear
Ordnance	O	3 yr	B, D, R, M	IEP, expansion, protection, better match	Machine tools	Preservation of knowledge lost due to cuts
Semiconductors	G	5 yr	Burial only with current process technology	Unclear with current process technology	Wartime hardware, software demand	Development of process technology towards expansion and protection

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[412] A: mostly abroad; G: mostly global; O: mostly onshore

[413] B: burial, R: revetment, D: dispersal, M: mobility

[414] IEP: Increased efficiency through pull

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