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# Management and Business Review

## Preparing for a World Transformed

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- Global Challenges of Climate Change and Living Standards
- Analytics and the Digital Organization

# Digital Operations:

## Autonomous Automation and the Smart Execution of Work

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*By digitizing operations, companies may replace manual work with increased automation, but they may also augment human work through smarter execution. Robert Boute and Jan Van Mieghem present a conceptual framework that distinguishes the different levels of digitization, automation, and intelligence. This framework can serve as an audit, helping companies to assess where they are now and where they could be in the future.*

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The integration of digital technologies into the running, managing, and planning of organizations is growing steadily. We have developed a framework to structure our understanding of what digitization means for the operations of individual companies. Operations refers to the repetitive activities that comprise an organization's process. Our framework separates two important dimensions of digital technologies: those that facilitate automation or the autonomous execution of work, and those that use smart control algorithms to make *how* the work is executed more intelligent. Managers we have worked with found the framework useful as a diagnostic tool that reveals how an organization's work is currently being executed and how digitization may change that in the future.

To perform a task, operators follow the work instructions on their laptops or mobile devices. Good work instructions reduce mistakes and ensure uniformity of execution, which increases the company's quality and efficiency.

## Digital Operations: What's in a Name?

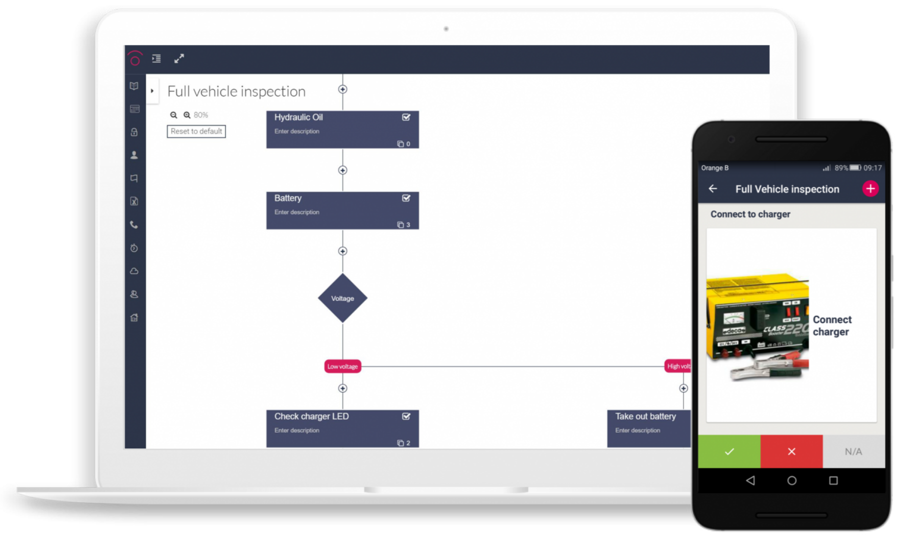
Digital operations means that a company's workflow (that is, its sequence of activities) is digitally supported, if not fully digital.[1] Digital operations must therefore start with digitizing the process flow, including all work instructions. The Belgian company Proceedix, for example, moves clients' workflows from paper to digital form. To perform a task, operators then follow the work instructions on their laptops or mobile devices. Good work instructions reduce mistakes and ensure uniformity of execution, which increases the company's quality and efficiency. These digital work instructions are also easily customized and allow the organization to manage complexity more effectively and provide greater variety.

| Digital Levels | |
|---|---|
| 0. | Not computerized |
| 1. | Siloed application |
| 2. | Enterprise data platform |
| 3. | Internet-web-based platform |
| 4. | Cloud-based platform |
| 5. | Connected devices/mobile/wearable |

A company's workflow can be digitized as a siloed application on an individual electronic device, which we refer to as digital level 1. A spreadsheet, for instance, digitally supports the workflow, yet may not be integrated or otherwise communicate with other applications or information. Higher levels of connectivity lead to higher levels of digitization. Level 2 describes moving the workflow and the data to an enterprise platform which can collect, synchronize, and integrate data across the company's various activities. 7-Eleven Japan, for example, set up its own connected enterprise data platform before the Internet protocol was widely adopted in industry.

At level 3, the platform is accessible over the Internet and standard Internet protocols introduce new possibilities including web-based applications, remote assistance, and connectivity with third-party apps. By giving operators web-based access to a central platform, Proceedix enables remote assistance and communication of digital work instructions. At level 4, the platform becomes more scalable because it is hosted in the cloud, for example through Amazon Web Services (AWS), Google Cloud Platform, or Microsoft Azure.

Finally, at digital level 5, also referred to as a *digital control tower*, companies can view real-time data from physical devices connected to the Internet—-the *Internet-of-Things* (IoT)---and from the mobile and wearable communication devices that



allow the so-called *Internet-of-People* (IoP) to function. The European rail-freight and logistics company Lineas monitors its locomotives in real time. Its sensors not only track the location of assets, but also monitor their condition. Lineas combines all this information into a *digital twin* of its physical operation which allows the company to conduct predictive diagnostics and maintenance. These *cyber-physical systems (CPS)* are key elements of Industry 4.0, a term which originated in Germany to describe the fourth industrial revolution. The distinguishing feature of CPS is extensive real-time connectivity through IoT and IoP. The latter is vital in allowing digital systems to capture human intervention, an information flow which is seldom recorded in any detail in paper or even PDF instructions. When digital workflow instructions include "inspect" followed by "report," for example, inspectors or repair operators can immediately upload their inspection findings and interventions from the field (by text, voice, or image) using their mobile devices. This manual IoP data augments the IoT data automatically captured by sensors and can also serve as feedback data for further improvement. IoP also allows the system to generate personalized digital work instructions (e.g., adjusted for the operator's experience) which can accelerate high-quality onboarding, training, and task execution.

While higher levels of digitization open up new opportunities, it is important to keep in mind the downside of using an Internet-enabled platform: cyber risk and ransomware. In January 2020, Picanol Group, a producer of weaving machines, had to close plants in Belgium, China, and Romania for more than a week after a cyber attack. Cyber risk has risen to become the most important danger to global business in the 2020 Allianz Risk Barometer and managers are becoming ever more aware of it.

Digital workflows, and digital operations in general, present a progression of new opportunities from real-time monitoring and visualization to analysis and optimization using advanced algorithms, and perhaps artificial intelligence. The dizzying array of possibilities leaves organizations wondering how to participate in this digital transformation. It also drives a societal debate on the impact of artificial intelligence on human work. In both of these cases, we believe it is useful to disentangle the effects of automation and autonomy from those of smart control and artificial intelligence.

> Digital operations facilitate the automation of work, allowing the work to be performed by a machine instead of a human. That machine may be a programmable mechanical device such as a robot, or a software application that performs automated tasks, known simply as a bot.

## Automated and Autonomous Operations

Digital operations facilitate the automation of work, allowing the work to be performed by a machine instead of a human. That machine may be a programmable mechanical device such as a robot, or a software application that performs automated tasks, known simply as a bot. For example, as ever more financial transactions are tracked and integrated digitally, Spanish tax authorities have gained sufficient data to allow a bot to automatically fill out tax forms. In a product supply chain, automated digital operations might include automatic periodic preventive maintenance or replenishment. Amazon Prime customers can thus sign up for automatic monthly delivery of consumables like toilet paper. Computer numerically controlled (CNC) machines, such as 3D printers for additive manufacturing and digitally controlled flexible manufacturing systems (FMS), are also examples of digital automation.

> Digital operations do not necessarily mean that the work is automated. Similarly, automation does not necessarily involve digital autonomy.

Nonetheless, digital operations do not necessarily mean that the work is automated. We can file our taxes digitally by downloading the necessary tax forms, filling them out manually on a computer or smartphone, and submitting them electronically.

Similarly, automation does not necessarily involve digital autonomy. The automation of the first industrial revolution clearly preceded the computer age. Its machines could not sense their environment or run autonomously, so they required human supervision. Autonomy means acting alone, following your own laws or control and not being under the rule of another.

Automation and autonomy came together a century ago when Sakichi

| Levels of Automation & Autonomy | |
|---|---|
| 0. | No automation (no machine or bot) |
| 1. | Automation with human control/ supervision |
| 2. | Automation with conditional autonomous control |
| 3. | Automation with autonomous control in certain environments |
| 4. | Automation with full autonomy |

Toyoda invented a powered textile loom with an automatic stopping device. A mechanical sensor automatically and immediately stopped the loom when the thread broke or ran out. This innovation reduced the production of defective products and greatly improved labor productivity. Because the machines no longer required continuous supervision, one human could supervise many machines. This concept of autonomous or intelligent automation was named *jidoka* or "*autonomation*" and became a cornerstone of the Toyota Production System. Autonomous automation describes machines that are capable of operating without direct human control or intervention.

The distinction between automation and autonomy highlights the role and location of *control rules.* Every task in an operation requires a control rule (or *algorithm*) dictating when and how the task should be performed. Inspired by the taxonomy of the Society of Automotive Engineers, we distinguish four levels of automation and autonomy. Automation with human supervision, level 1, separates the human control from the machine. For example, a credit card application process includes various customer credit checks. The computer prompts a checklist and the bank manager makes a decision about each check.

Level 2 embeds the control within the machine, giving the machine autonomy in certain conditions but requiring human intervention in others. Toyoda's loom, for example, ran autonomously as long as the thread did not break or run out. Likewise, credit card applications are automatically approved as long as the customer's credit score, employment history, and income level are sufficiently high and outstanding debt, number of credit cards, and requested credit card limit are sufficiently low. If these conditions are not met, the system requests human intervention in the approval decision.

Level 3 is automation which is fully autonomous in a given environment. The credit card approval process is totally automatic only in certain cities, counties, or states where all credit card application information is available and trustworthy.

Level 4 describes automation which is entirely autonomous in all environments. This would include autonomous vehicles without steering wheels and other automation that cannot be overridden by human intervention. The precise distinctions between these levels are debatable since it depends on how frequently, easily, and quickly humans can and do override the automation.

## Smart Operations

Digital operations can improve the intelligence of the control rule. It can make control rules adaptive, contingent, dynamic, and personalized, creating control rules that can sense and learn by using state variables and observations. We refer to control rules or algorithms that embed intelligence as *smart.*

| Smart Levels | |
|---|---|
| 0. | No feedback-control |
| 1. | Explicit instructions contingent on one feature |
| 2. | Explicit instrtructions contingent on multiple features |
| 3. | Machine learning |

**Prediction $Y = f(X) + \varepsilon$**

= given features *X*, predict *Y* using a mapping function f

- Prediction error = ε
- Supervised = *f* was trained on labeled historical data
- Deep learning = *f* is a deep neural net

Condition-based preventive maintenance is smart because it schedules inspection or repair based on the actual condition of the machine. Preventive maintenance on a set schedule, by contrast, is not smart because it does not use any adaptive feedback control.

We distinguish three levels of smart control. Smart level 1 or 2 describes a control rule or algorithm which consists of a sequence of explicit instructions that are contingent on, respectively, one or multiple input variable(s) or *features*. In inventory management, a system which decides the replenishment quantity and time only on the basis of bringing current inventory up to a set target point is smart level 1. A decision tree that consists of multiple if-then instructions with regard to multiple features--e.g., the *expert systems* of the 1980s--is smart level 2. Similarly, the automated guided vehicles which have operated along premarked routes in warehouses for decades are also level 2. They are controlled by exhaustive explicit if-then instructions, and so can only function in highly restricted environments. In May 2019, a 12m-long uncrewed boat crossed the North Sea autonomously. It relied on multiple sensors (sonar, radar, lidar, camera, infrared, GPS, etc.) to safely navigate one of the busiest shipping lanes in the world.

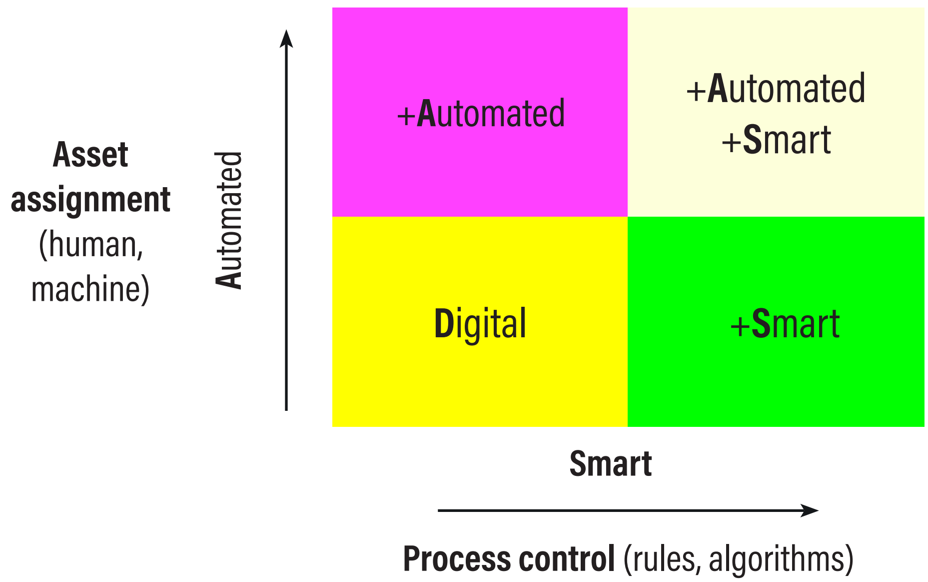
When the number of combinations in the input variables of the control algorithm explodes, enumerating explicit instructions becomes infeasible. Smart level 3, then, refers to machine learning algorithms which effectively perform a specific task without using explicit instructions, relying instead upon patterns and inference.

In order to drive autonomously in unrestricted environments, the system relies on machine learning algorithms, called *prediction machines,*[2] that predict what a human driver would do given specific road conditions. The prediction machine bases its decisions on labeled training data consisting of many observations of human behavior (actions) at specific values (states) of environmental variables (features). For highly complex prediction problems, machine learning can utilize a *neural network* with multiple layers between input and output, which mirrors the human brain. This process is known as *deep learning* and is the basis of many image recognition systems.

In addition to predicting events, such as machine breakdowns or transport delays, machine learning algorithms can also *prescribe* (near-optimal) actions. The ancient game of Go is played on a board with 19 x 19 = 361 positions (features) each of which can contain a black, white or no stone. It therefore has $3^{361}$ = about $10^{172}$ possible states, more than the number of atoms in the universe. Devising explicit instructions (prescriptions) for how to play each state is therefore impossible. (In mathematical terms, the optimal value function of the Markov decision problem cannot be solved for precisely.) One branch of machine learning thus uses and refines an approximate (value) function from which the system can derive a recommended action for any state. This mathematical approach yields a machine learning algorithm that makes its own decisions and hence is described as *artificial intelligence*. The first machine learning algorithm to beat 9-dan ranked professional Go player Lee Sedol in March 2016 was AlphaGo. It used a thirteen layer neural network to select moves. The same deep learning algorithms can be used to make replenishment decisions in a complex environment with many suppliers or channels, or to make optimal transport decisions based on current traffic information.

Adopting machine learning typically requires (1) a large training data set through which the system can estimate, fit, or tune the algorithm and (2) data for the actual prediction. Electric car manufacturer Tesla also uses (3) feedback from drivers to improve the prediction accuracy. Companies often invest extensively in IoT in order to use the resulting data for predictive analysis. But IoT by itself does not capture how humans respond to a request or alarm from a smart system. The use of digital workflows allows the system to capture these human interventions which comprise the aforementioned IoP. It thus extracts data on which interventions were made, by which operator, to address which request, or was this a false alarm. This feedback data can be used to improve the algorithms. Digitizing operations is therefore a prerequisite of smarter operations and the implementation of machine learning.

**Figure 1:** By distinguishing smart process control from human-machine assignments, the DAS framework for digital operations provides the visualization and vocabulary with which to discuss future strategic directions.




## DAS Framework for Digital Operations

The DAS framework synthesizes three perspectives on operations: digital, automated, and smart.

### *Diagnostic*

The DAS framework can serve as a diagnostic, allowing organizations to assess the current state of their digital operations. This assessment can focus on any number of specific processes, or even the entire value chain, evaluating each task along the three dimensions and assessing them according to the rubric in Exhibit 1. A company could thus focus on assessing the digitization of customer interaction, collecting customer input data to personalize successive steps in the process. By bringing the customer interaction inside the value chain and explicitly capturing how goods and services are marketed to customers, the company can personalize its product offerings and price in real time. For example, while selling and approving home and renter's insurance, the Lemonade Insurance Company digitizes and personalizes its customer interactions. The firm can use the diagnostic to assess a range of internal processes, as well as outbound logistics or customer service. The Lemonade Insurance Company also uses bots rather than insurance brokers to handle claims.

Note that not all 5 x 4 x 3 = 60 combinations of digital, automated and smart levels are necessarily feasible. A siloed spreadsheet application, for instance, is unlikely to generate sufficient data for machine learning analysis.

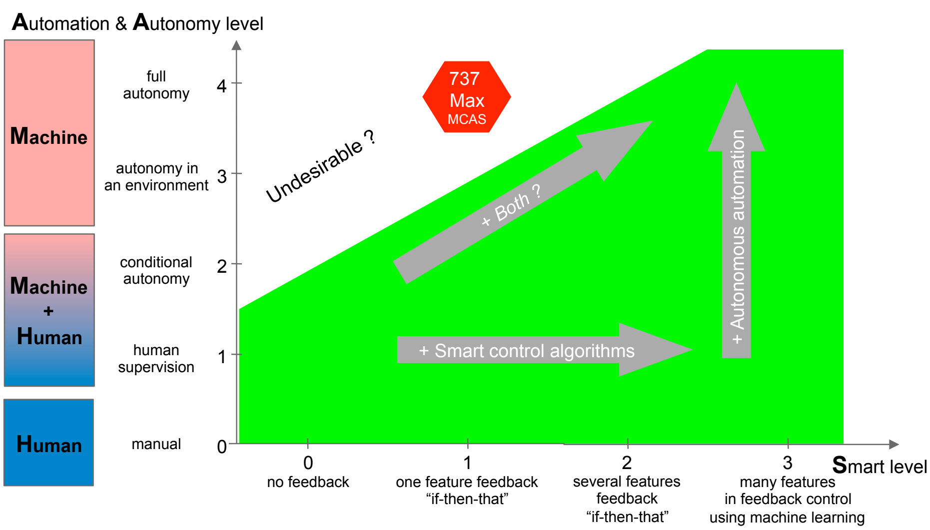
### *A framework for future directions*

For simple automation that does not require autonomy, the DAS framework can be summarized by the 2 x 2 matrix in Figure 1. The four quadrants provide a visualization and vocabulary through which companies can discuss where their digital strategies can, and more importantly should, take them next. Exhibit 2 adds non-digital strategies, defining seven zones according to the intersections of our three perspectives on operations while also providing concrete examples in the context of order replenishment.

Digital operations facilitate smarter control rules or algorithms by capturing and storing big data, that is, data sets with many observations (rows) or many features (columns), from digital transactions or physical sensors. In Figure 1, this ability is represented by moving from the pure digital quadrant to the digital+smart quadrant. For example, Pacif-i sells a pacifier which contains a Bluetooth temperature sensor so you can remotely monitor your baby's temperature. This feature enables a concurrent statistical process control to send alerts. Tracking and storing time-stamped data allows the system to train its machine learning algorithms in order to improve pattern recognition and make alerts smarter (e.g., based on the speed of the baby's temperature change). As the algorithm becomes smarter, its predictions become more accurate. Eventually, the system could automatically request medical intervention.

Digital operations may also facilitate simple *robotic process automation* (RPA). RPA can start by tracking human clicks while operators perform a tedious task on a computer and then train an algorithm to perform that same task faster, cheaper, and more accurately. The Romanian company UiPath has adopted an "automation first" approach to digital transformation. In Figure 1, this trajectory is represented by moving from the pure digital quadrant to the digital+automated quadrant. Relieving humans of tedious tasks frees up their creativity and time for higher-value tasks.

**Figure 2:** For complex automation, one should only proceed to higher levels of autonomy if the smart control rule's prediction accuracy is sufficiently high and the downside risk of autonomous automation is sufficiently low.



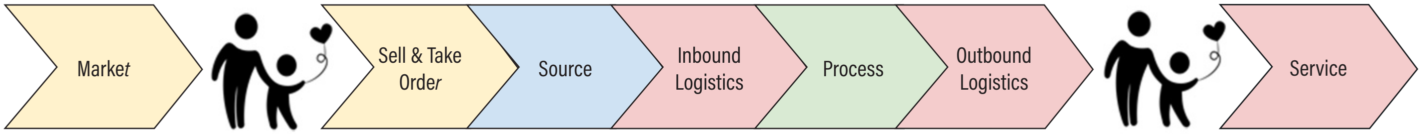

It is important to recognize that moving to different quadrants in the framework requires companies to invest in different human abilities.

It is important to recognize that moving to different quadrants in the framework requires companies to invest in different human abilities. Digitizing operations requires workers with knowledge of computer science, databases, software development, user interfaces, and information technology. Using smart algorithms requires workers who specialize in operations research and data science to run analytics, statistics, and optimization. Automation requires workers who understand mechanical and electrical engineering as well as computer science to build physical robotics and software bots.

### *Autonomy and Human-Machine Collaboration*

For simple automation that does not consider autonomy, the 2 x 2 matrix in Figure 1 may be a sufficient diagnostic. For example, whether you set your coffee-maker on automatic mode is a simple 0 – 1 decision. In manual mode, you turn the coffee maker on at 6am; in automatic mode, you set a timer in advance that will automatically turn the machine on at the designated time. Because both the environment

**Exhibit 1** **Digital Operations Diagnostic Across the Value Chain**




### Digital

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 0. Not computerized | | | | | | | |
| 1. Siloed application | | | | | | | |
| 2. Enterprise data platform | | | | | | | |
| 3. Internet-web-based platform | | | | | | | |
| 4. Cloud-based platform | | | | | | | |
| 5. Connected devices/mobile/wearable | | | | | | | |

### Automation & Autonomy

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 0. No automation (no machine or bot) | | | | | | | |
| 1. Automation with human control/supervision | | | | | | | |
| 2. Automation with conditional autonomous control | | | | | | | |
| 3. Automation with autonomous control in certain environments | | | | | | | |
| 4. Automation with full autonomy | | | | | | | |

### Smart

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 0 No feedback control | | | | | | | |
| 1. Explicit instructions contingent on one feature | | | | | | | |
| 2. Explicit instructions contingent on multiple features | | | | | | | |
| 3. Machine learning | | | | | | | |

and the automation are limited, there is no need to capture the autonomy's degrees of freedom.

For more complex automation with autonomy, we need more nuance and depth in the matrix. We gain more insight by adding the more specific levels of automation, autonomy, and smart control, as in Figure 2. For a car to drive autonomously, we must ask what control inputs it requires and how the environment will evolve so that optimal control becomes a dynamic, adaptive function of the state space. Companies should only proceed to higher levels of autonomy once the control rule can predict with sufficient accuracy.

Smart algorithms can provide decision support to human workers. This kind of improvement of the symbiosis between human and machine through smarter control rules constitutes a horizontal increase in Figure 2. As the smart control algorithms improve their accuracy, they may become more trustworthy so that their downside risk is contained. The company may then move toward automation with increasing autonomy. This process equates to vertical increase in Figure 2, from manual or human-supervised machines to autonomous ones. Companies may also choose to increase autonomy and smart control simultaneously (ie., moving up the diagonal) but to do so, they must apply multiple human capabilities simultaneously.

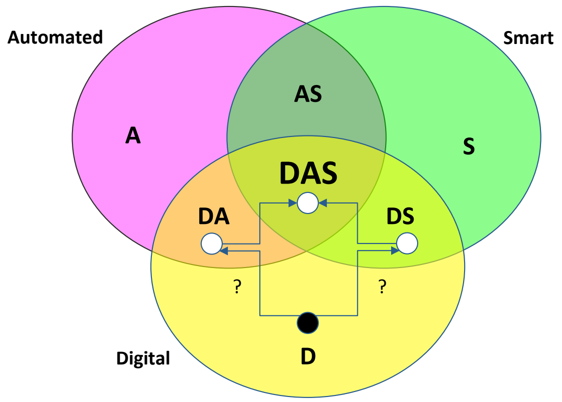
It is vital that designers always retain human oversight and high redundancy in systems with large downside risk.

The key implication of this framework is that the upper left zone is undesirable, and sometimes even dangerous. On October 29, 2018

**Exhibit 2: Adding non-digital strategies yields seven zones, illustrated for order replenishment**

Allowing for non-digital strategies yields seven zones, derived from the intersections of the three perspectives—digital, automated, and smart—on operations (Fig. 3). Like the quadrants, the seven zones, together with the earlier defined levels, provide a visual and a vocabulary with which to discuss the future of the organization's digital journey ("where can we go?" or more strategically, "where should we go?"). As a specific example of the seven zones, consider the order replenishment process. First we define the three circles, and then the seven zones created by their intersections.

**Figure 3:** Intersecting the three perspectives on operations--digital, automated, and smart---yields seven zones.




Circle Digital = human operator digitally orders from the supplier using a siloed application (e.g., spreadsheet, email) on their personal device (digital level 1). Digital levels 2, 3 and 4 refer to the data and the order being integrated into an enterprise platform. Digital level 5 refers to the operator being able to see the supply chain in real time through digitally-captured data (control tower).

Circle Smart = the ordering decision uses an explicit inventory control rule, which can depend on only the inventory status (smart level 1) or on multiple inputs such as inventory on hand, age of the inventory, inventory in transit, and demand forecasts (level 2). Smart level 3 means that the inventory control rule is derived using machine learning.

Circle Automated = the ordering decision is suggested automatically by a bot and is approved by an operator (level 1). Conditional on the values of the item's features (e.g., its type, unit cost, demand rate, forecast accuracy), the order is placed automatically and autonomously (level 2). Level 3 refers to automatic, autonomous order placement for any item in pre-defined product families; and level 4 for all products.

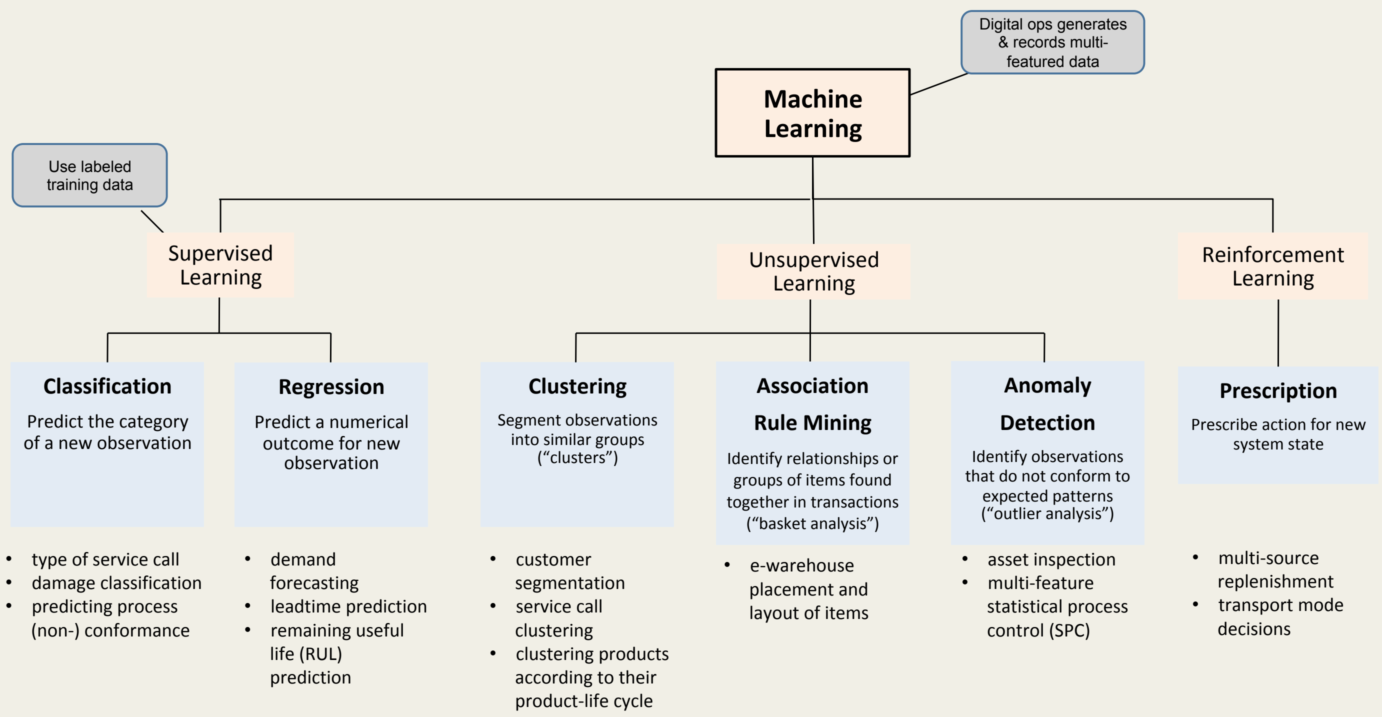
The seven zones now follow from set algebra:

1. D = digital order replenishment process executed by a human operator based on personal experience; i.e., without using an explicit, or machine learning generated, control rule.
2. S = conventional, non-computerized order replenishment process executed by an expert human operator utilizing an explicit control rule relying on data that is non-digitally captured. (Note, by definition, smart level 3 is impossible in a non-digital setting.)
3. A = automated ordering that is neither computerized nor smart; e.g., daily (time-based) milk delivery.
4. DA = time-based automatic digital ordering (e.g., Amazon Prime weekly delivery)
5. DS = digital order replenishment process executed by a human operator utilizing an explicit control rule relying on data that may be digital. (Machine learning is now possible through digital data.)
6. AS = automated ordering that is not computerized but utilizes a smart control rule; e.g., consumption-based automatic ordering perhaps using an analogue sensor of inventory status.
7. DAS = digital, automated, smart order replenishment.

and March 10, 2019 respectively, it should have been much easier for the pilots of Lion Air's flight 610 and Ethiopian Airlines flight 302 to override the Boeing 737 MAX's MCAS flight controls, a system which tragically depended on only one sensor (the angle of attack). It is vital that designers always retain human oversight and high redundancy in systems with large downside risk.

Human oversight is also important wherever people prefer or expect human involvement. KLM Royal Dutch Airlines became a front-runner in digital operations by emphasizing smart control over automation. The company touts its use of "data and advanced analytics to coordinate decision making involving fleet and ground operations, maintenance, crew, and passenger needs, for every flight every day." It has learned that "optimizing operational performance can never be fully automated. Although companies need the right systems in place, even a theoretical best-in-class carrier—armed with state-of-the-art processes, data, and technology—requires employees to apply good judgment and make smart decisions."[3]

**Exhibit 3: Machine Learning Tasks & Digital Ops Examples**




## The Business Case for Digital Operations

Of course, each company's starting position and ideal direction of movement in the framework are unique and should be informed by a strategic assessment and a cost-benefit analysis.

Companies should weigh the incremental cost to increase the level of digitization, automation and autonomy, and smart control against the incremental need and benefit of the improved quality, accuracy, speed, personalization and choice, or reduced cost.


For example, non-invasive prenatal testing (NIPT) predicts the likelihood that a developing fetus will be born with certain genetic anomalies. In contrast to invasive procedures like amniocentesis, NIPT does not increase the risk of miscarriage. Moreover, NIPT uses digital DNA sequencing that generates lots of data which can then be used to train machine learning algorithms that, in turn, improve prediction accuracy and detect additional genetic anomalies. This last factor was the main motivation for the Center for Human Genetics at the University Hospitals Leuven, Belgium, to become a world-leader in NIPT as of 2013.

Because of the improved quality and the continual reduction in the cost of DNA sequencing, Belgian health insurance systems began covering NIPT on July 1, 2017. There was a three-fold increase in the demand for NIPT over the subsequent year, which the Center met by automating the analysis process, which consists of DNA extraction from plasma, preparation and sequencing, and bioinformatic analysis. As the volume of data generated increased, the system's prediction accuracy improved. This reciprocity resulted in a virtuous cycle of growth in throughput, quality, and diversity of genetic anomalies screened while reducing the cost per NIPT test by more than 50 percent over five years.

## Call to Action

Digitizing operations presents a plethora of opportunities. Exhibit 3 gives examples of how machine learning can improve work. We

| The Operations Improvement Sequence | |
|---|---|
| 1. | Value Stream Map your process and standardize |
| 2. | Reduce waste by humans and machines |
| 3. | Optimize |
| | Only then: |
| 4. | Digitize and automate |
| | (otherwise you automate waste) |

caution, however, that the fundamentals of good operations management remain. **First, before digitizing or automating, streamline, standardize, and optimize your workflows,** or you may end up automating waste.

**Second, focus on data quality and quantity.** Develop a data strategy that will allow you to collect and capture, organize, store, and maintain data. Reliable data is a prerequisite for effective smart control rules. We have found that collecting trustworthy quality data can be very challenging. Once your internal quality data is properly organized, you may wish to consider a federated database system to share data while protecting confidentiality.

**Third, prepare your organization for a data-driven culture which augments human work.** Clearly, workers are more likely to accept and trust a system if it shows high prediction accuracy in its data-driven recommendations, let alone prescriptions. Nevertheless, even automation with human supervision or conditional autonomy (levels 1&2) can provide substantial benefits which will encourage worker buy-in and support.

**Fourth, invest in new human capabilities: knowledge and skills.** Recall that increasing automation requires different capabilities from increasing smart controls. A strategic move between quadrants in the framework should thus include investment in different knowledge and skills.

## Conclusion

Digital operations create new strategic opportunities. By adopting smart control and artificial intelligence, companies can *augment* human work and improve the quality, speed, variety, and personalization of their products or services. Digital also facilitates automation, but before considering higher levels of autonomy, companies must establish smart control with high prediction accuracy. We recommend exercising serious caution before eliminating all human intervention, especially in situations with high downside risk.

Establishing digital operations, whether they be smarter or more automated, can lead to increased demand and even open up new business opportunities. This process may eliminate some jobs but may also create new ones. For example, by partially automating NIPT procedure, the Center for Human Genetics has increased its clinical and non-clinical staff, bioinformaticians, and software engineers and continues to recruit intensely. We hope that our diagnostic tool can inspire debate on how digitization may be put to best use in the future.

In this article we have focused largely on routine operations with high frequency workflows that can readily be codified for smart control algorithms and automation. We recognize that there are larger strategic questions which we have not addressed, including how to support a leadership team as it digitizes higher level cognitive tasks and processes. The interactions between human judgment and automation are more complex in knowledge-intensive work, such as negotiation or strategy formulation workshops that are not easily reduced to a flow chart. Streamlining such complex processes calls for extensive and fascinating future research. ■

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## Endnotes

1. Digital means represented by numbers or, colloquially, computerized. The word digital is derived from the Latin word *digitus* meaning finger. Counting on your fingers led to a digit being one of the elements that collectively forms a system of enumeration. Operations derives from the Latin word *opus* meaning work.
2. *Prediction Machines, The simple economics of Artificial Intelligence.* Agrawal A., Gans J. and Goldfarb A. Harvard Business Review Press, 2018.
3. *How Digital Operations Put The World's Oldest Airline In The Lead.* Boston Consulting Group report. https://www.bcg.com/publications/2019/how-digital-operations-put-worlds-oldest-airline-lead.aspx