An Architecture for a Cyber-Physical Healthcare Delivery System with Human Agents

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***Abstract*—The traditional monolithic hospital focused healthcare system organically developed to address acute conditions. In recent years, healthcare needs have shifted from treating acute conditions to meeting an unprecedented chronic disease burden. The long-term complex nature of chronic diseases imposes requirements on 1.) the individual: to actively participate in their healthcare rather than only passively receive treatment(s) and 2.) the healthcare system: to evolve towards an intelligent, cyber-physical system capable of smart data acquisition both within and outside the clinic to provide care *when* and *where* the individual requires it. This presents a formidable systems challenge where the state of the healthcare delivery system must be coordinated over many years or decades with the health state of each individual that seeks care for their chronic conditions. This paper architects a system model for personalized healthcare delivery and managed individual health outcomes. To ground the discussion, the work builds upon recent structural analysis of mass-customized production systems as an analogous system and then highlights the stochastic evolution of an individual's health state as a key distinguishing feature. Architecting a coordinated system model such as this one opens several avenues for future work to develop and detail the effects of the cyber-physical nature and the latest data acquisition systems of the healthcare system on health outcomes and cost.**

***Index Terms*—system architecture, healthcare delivery system; individual health outcomes;**

I. Introduction

Industrial systems are often studied in terms of their structural topology. While this includes "hard" infrastructure, such as water, power, and transportation, it is important to include "soft" infrastructure [1], such as the healthcare system.

The current healthcare delivery system organically developed to meet "one-off" acute conditions, however, it is now facing an unprecedented chronic disease burden. These conditions, are particularly complex – they are ongoing and tend to involve multiple factors with multiple interactions between them [2].

Relative to acute conditions, characteristics of chronic conditions present several new healthcare delivery challenges. Four are identified in Table I.

To further distinguish between acute and chronic healthcare delivery, this work refers to "individuals" rather than patients. The former addresses people throughout their lives in general whereas the latter addresses their state when they are in a healthcare delivery facility.

Thus, the characteristics of chronic diseases require much more from the operation of a healthcare delivery system than the way it has operated to address acute conditions within individual visits. Instead, the four characteristics presented in Table I present four new requirements on the healthcare delivery system, see Table II. Fulfilling the requirements fundamentally changes, not just the relationships between the individual and the healthcare delivery system, but also the relationships between its many services and resources as well. These relationships suggest the need for system tools [3] for architecting a system model for personal healthcare delivery and managed individual health outcomes.

TABLE I
Healthcare Delivery Challenges for Chronic Conditions

1) First, by definition, chronic disease is described by a sequence of events that (d)evolve an individual's health state over a duration that is often far longer than any single visit to a healthcare facility.
2) Second, the sequence of these events do logically depend on each other as described by medical science.
3) Third, how any individual experiences this chronic condition is often entirely unique given their unique combination of social, behavioral, environmental & biological risk factors.
4) Finally, this chronic condition often affects many aspects of an individual's health that are often covered by disparate medical disciplines.

TABLE II
New Healthcare Delivery System Requirements

1) Continues to deliver care well after the individual has left the healthcare facility.
2) Deeply understands the health state of the individual.
3) Manages individualized health outcomes.
4) Coordinates numerous practitioners representing many medical specialties.

While this strategic shift in healthcare delivery systems may appear dramatic, it is not without precedent in other domains. Mass production systems underwent a similar transformation to become mass-customized production systems [4], [5]. Reconfigurable manufacturing systems, in particular, required a re-architecting of production systems in favor of modular machine tools and distributed control systems in the form of multi-agent systems [6]. In time, these new architectural developments were situated within quantitative graph theoretic frameworks [7]–[10] and used to design new mass-customized production systems [11], [12]. This quantitative foundation now lends itself to reapplication for personalized healthcare delivery.

This paper architects a systems model for personal healthcare delivery and managed individual health outcomes. To support the development, it specifically roots itself in recent work on the architecture of mass-customized production systems and then incorporates features specific to healthcare delivery. This model directly addresses the four requirements derived from the characteristics of chronic diseases. Special attention will be given to the description of an individual's

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health state and its stochastic evolution in relation to the healthcare delivery system. This is in contrast to many existing works [13], particularly in healthcare discrete event simulation, where the individual is treated as a stateless passive entity (e.g. a petri-net token) being pushed or pulled through various healthcare system queues.

The paper begins with the description of the Architecture Model (Section II) followed by the Discussion & Conclusion (Section III). The work assumes prerequisite knowledge in model-based systems engineering [14], [15], graph theory [16], and discrete-event simulation [17] which is otherwise gained from the cited texts.

II. Development of Architecture Model

The development of the architecture model proceeds in five parts following Figure 1. Based on systems engineering texts [18], [19], the healthcare delivery system is characterized by its form, function and concept. Section II-A describes the system form as a set of human and technical resources that make up a physical architecture. Section II-B describes the system function as a set of system processes the make up a functional architecture. Section II-C describes the system concept as an allocated architecture composed of a bipartite graph between the system processes and resources. Section II-D then introduces a discrete-event Petri-Net model describing the evolution of an individual's health state. Here, the individual represents the primary value-adding operand of the healthcare delivery system. It's introduction addresses the first three requirements identified in the introduction. Finally, Section II-E introduces a bipartite graph that links the healthcare system function to the evolution of an individual's health state. The quantitative discussion draws heavily on analogous works on mass-customized production systems [7]–[12].

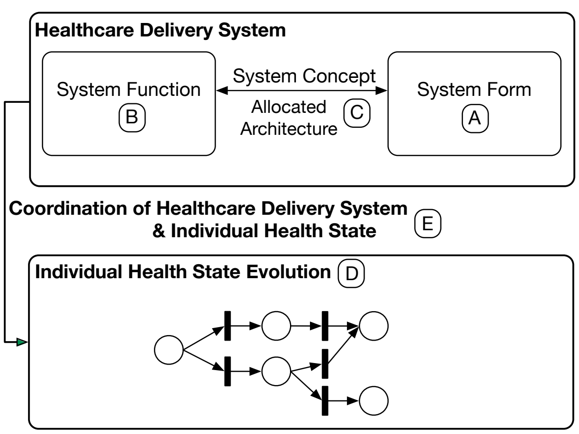

Fig. 1. **Healthcare System Architecture includes the Healthcare Delivery System, the Individual Health State and their Coordination.**

A. Healthcare System Form: Systems Resources & their Flexible Aggregation

To begin, the healthcare system form [18] (shown as A in Figure 1) is composed of several types of system resources which may be flexibly aggregated. In mass-customized production systems, the system resources were classified as transformation resources (i.e. value-adding machines), storage resources (i.e. independent buffers), and transportation resources (i.e. material handlers) [7]–[12]. Each of these has their analogous counterparts in the healthcare delivery system. That said, the healthcare delivery system requires a finer classification of its system resources. These include the definition of measurement & decision resources as well as the distinction between human and technical resources.

Definition 1. Transformation Resource: A resource $\mathbb{r}_F \in \mathbb{R}_F$ capable of a transformative effect on its operand (e.g. the health state of an individual). They include *human* transformation resources $r_F \in R_F$ (e.g. surgeon, cardiologist) and *technical* transformation resources $\mathscr{r}_F \in \mathscr{R}_F$ (e.g. operating theaters, delivery room). Transformation resources are the set union of human and technical transformation resources, $\mathbb{R}_F = R_F \cup \mathscr{R}_F$.

Definition 2. Decision Resource: A resource $\mathbb{r}_D \in \mathbb{R}_D$ capable of advising the operand, an individual, on how to proceed next with the healthcare delivery system. They include *human* decision resources $r_D \in R_D$ (e.g. oncologist, general practitioner) and *technical* decision resources $\mathscr{r}_D \in \mathscr{R}_D$ (e.g. decision support systems, electronic medical record decision tools). Decision resources are the set union of human and technical decision resources, $\mathbb{R}_D = R_D \cup \mathscr{R}_D$.

Decision resources are analogous to storage resources in previous work on mass-customized production systems [7]–[12] but are different in two regards. First and fundamentally, in production systems a shop-floor controller (be it automatic or manual) often dispatches a passive product. Naturally, within the medical community, an individual is viewed as an active stakeholder-participant. In this regard, recent work on "intelligent products" [20], [21] in mass-customized production systems is a much more appropriate analogy. Such "intelligent products" are cyber-physical entities that consist of a physical product tied 1-to-1 with an informatic agent that is capable of negotiating and coordinating with the production system. Second, in production systems, intelligent products do not need to be in a specific location to be part of decisions for the next steps of production. In contrast, individuals must often meet healthcare professionals face-to-face in order to determine next steps.

Definition 3. Measurement Resource: A resource $\mathbb{r}_M \in \mathbb{R}_M$ capable of measuring the operand: here the health state of an individual. They include *human* measurement resources $r_M \in R_M$ (e.g. MRI technician, sonographer) and *technical* measurement resources $\mathscr{r}_M \in \mathscr{R}_M$ (e.g. magnetic resonance imaging scanner, ultrasound machine). Measurement resources are the set union of human and technical measurement resources, $\mathbb{R}_M = R_M \cup \mathscr{R}_M$.

Measurement resources are analogous to storage resources in previous work on mass-customized production systems [7]–[12]. In production systems a product's state is relatively well-known from the course of its production. Storage resources are required to simply account for a product's location. In contrast, an individual's health states needs to be explicitly ascertained by the healthcare delivery system. The analogy to production system storage resources is retained because naturally this measurement must occur at well specified locations in the healthcare delivery system.

Definition 4. Transportation Resource: A resource $\mathbb{r}_N \in \mathbb{R}_N$ capable of transporting its operand: the individual them self. They include *human* transportation resources $r_N \in R_N$ (e.g. emergency medical technician, clinical care coordinator, surgical team member) and *technical* transportation resources $\mathscr{r}_N \in \mathscr{R}_N$ (e.g. ambulance, gurney, wheelchair). Transportation resources are the set union of human and technical transportation resources, $\mathbb{R}_N = R_N \cup \mathscr{R}_N$.

Transportation resources act much like they do in mass-customized production systems. However, healthcare transportation resources are only required when the individual cannot transport themselves unassisted within the healthcare delivery system.

Definition 5. Buffer Resource: A resource $r \in \mathbb{R}_B$ where $\mathbb{R}_B = \mathbb{R}_F \cup \mathbb{R}_D \cup \mathbb{R}_M$.

In order to support the discussion of transportation processes it is useful to introduce the concept of buffer resources. Collectively, they denote specified locations. In production systems, they were the set union of transformation and storage resources. Here, they are the set union of transformation, measurement and decisions resources.

It is often useful to view healthcare delivery system resources purely in terms of human and technical classifications.

Definition 6. Human Resource: A resource $r \in R$ where $R = R_F \cup R_D \cup R_M \cup R_N$.

Definition 7. Technical Resource: A resource $r \in \mathscr{R}$ where $\mathscr{R} = \mathscr{R}_{\mathscr{F}} \cup \mathscr{R}_{\mathscr{D}} \cup \mathscr{R}_{\mathscr{M}} \cup \mathscr{R}_{\mathscr{N}}$.

The healthcare delivery system resources described thus far allows specific instances to be non-uniquely classified. In the cases where a resource is capable of performing several processes, it must be uniquely classified. For example, a surgeon is trained and defined by their transformation ability and not just their decision capability. In order to create a unique classification of these resources, a set of ordered classification rules are implemented.

Definition 8. Classification Rules for Healthcare Resources:

Rule 1: If $r \in R$ can *Transform*; then $r \in R_F$. If $\mathscr{r} \in \mathscr{R}$ can *Transform*; then $\mathscr{r} \in \mathscr{R}_{\mathscr{F}}$.
Rule 2: If $r \in R$ can *Decide*; then $r \in R_D$. If $\mathscr{r} \in \mathscr{R}$ can *Decide*; then $\mathscr{r} \in \mathscr{R}_{\mathscr{D}}$.
Rule 3: If $r \in R$ can *Measure*; then $r \in R_M$. If $\mathscr{r} \in \mathscr{R}$ can *Measure*; then $\mathscr{r} \in \mathscr{R}_{\mathscr{M}}$.
Rule 4: Otherwise $r \in R_N$ and $\mathscr{r} \in \mathscr{R}_{\mathscr{N}}$

These rules effectively sort resources on the basis of capability value. It is assumed that with respect to value: Transform > Decide > Measure > Transportation. This prioritization is often referred to as "practicing at the top of your license".

As many healthcare systems have hundreds or thousands of personnel and equipment, it is useful to form aggregated resources $\bar{\mathbb{R}}$ [7], [8], [11], [22]. $\bar{\mathbb{R}} = A_R \circledast \mathbb{R}$ where $\circledast$ is an aggregation operator and A_R is an aggregation matrix [7], [8], [11], [22]. These aggregations are flexible & logical, and can be changed administratively. For example, an Orthopedic Care Team may include a surgeon, an anesthesiologist, nurses, surgical techs, residents/medical students and cleaning staff. Naturally, the composition of this aggregation can be changed at a later time. Healthcare resource aggregation is critical for allowing flexibility in the level of abstraction (i.e. individual, teams, departments, clinics, regions or state) of the system.

In summary, healthcare delivery system resources are the set union of these previously mentioned types of resources.

$$\mathbb{R} = R_F \cup \mathscr{R}_F \cup R_D \cup \mathscr{R}_D \cup R_M \cup \mathscr{R}_M \cup R_N \mathscr{R}_N \quad (1)$$

$$\mathbb{R} = \mathbb{R}_F \cup \mathbb{R}_D \cup \mathbb{R}_M \cup \mathbb{R}_N \quad (2)$$

$$\mathbb{R} = R \cup \mathscr{R} \quad (3)$$

B. Healthcare System Function

Healthcare system function [18], [19] (shown as B in Figure 1) is composed of several types of system processes which will ultimately be deployed by the system resources. In mass-customized production systems, the system processes were classified as two types: transformation and transportation [7]–[12]. Storage processes were considered as transportation processes with non-distinct origin and destination [7]–[12]. The focus was on *physical* processes that directly interacted with the value-adding operand – the mass-customized product. Analogously, transformation & transportation processes exist similarly in the healthcare delivery system as physical processes on the individual. The healthcare delivery system has several essential characteristics that requires a broader classification. Engineering systems literature often classifies processes into: transformation, transportation, storage, control and exchange [23]. Consequently, in healthcare, measurement processes are identified as a type of control process and collaborative decisions are identified as a type of exchange process. It is important to note that these are *cyber-physical* processes in that they require the physical presence of the value-adding operand (i.e. individual) as well as information flow between the individual and the healthcare delivery system.

As with mass-customized production systems [7]–[12], these system processes may be organized into a (generic) template model of healthcare system function. Sequentially,

1) **Measurement**: understand, quantify or classify state,
2) **Decision**: determine what to do & when,
3) **Transformation**: perform service(s) for the individual,
4) **Transportation**: move individual between any processes.

Definition 9. Transformation Process: A *physical* process $p_F \in P_F$ that transforms the operand: specifically the internal health state of the individual (i.e. treatment of condition, disease or disorder).

A transformation process typically changes the health state of the individual. Such processes include: surgical procedures (e.g. amputation, ablation) and therapeutic procedures (e.g. pharmacotherapy, chemotherapy, psychotherapy).

Definition 10. Decision Process: A *cyber-physical* process $p_D \in P_D$ occurring between a healthcare system resource and the operand: the individual, that generates a decision on how to proceed next with the healthcare delivery system.

Several types of decision processes exist in a healthcare delivery system. Planning is defined as the determination of *which* healthcare system processes need to occur for the individual (i.e. treatment plan). Scheduling is defined as *who/what* is going to perform that process and *when* (i.e. booking). Furthermore, *intermediate* and *dispatching* decisions are distinguished in that the latter serve to trigger physical activities to the individual, and the former do not.

As a physical process, the individual must be physically present at a healthcare system resource (buffer) and in that sense a decision process resembles a storage process. As an informatic (i.e. cyber) process, information is exchanged (both directions) between the individual and the healthcare system resource to support *collaborative* decision-making [24]. A critical aspect of shared decision making & information exchange includes resources educating the individual, thereby enhancing the individual's ability to make the best decisions.

Definition 11. Measurement Process: A *cyber-physical* process $p_M \in P_M$ that converts a physical property of the operand into a cyber, informatic property to ascertain health state of the individual.

Typical healthcare measurement processes acting on individuals include: clinical evaluation, diagnostic tests (e.g. blood test) and diagnostic procedures (e.g. medical imaging).

As a physical process, the individual must be physically present at a healthcare system resource (buffer) and in that sense a measurement process resembles a storage process. As an informatic (i.e. cyber) process, information is drawn from the individual to ascertain their health state (i.e diagnose). In mass-customized production systems, the state of each product is relatively well-known from the course of its production. In contrast, an individual's health state evolves stochastically and spontaneously. Understanding an individual's health state is one of the core functions or processes of the healthcare system, which it performs through measurement.

Definition 12. Transportation Process: A *physical* process $p_N \in P_N$ that moves individuals between healthcare resources (e.g. bring individual to emergency department, move individual from operating to recovery room).

Although individuals do not typically need to be moved (unless incapacitated), transportation processes are specifically included for the sake of completeness and adherence to the mass-customized production system analogy. This is also performed because it explicitly states the capabilities of the system rather than the utilization of the system by the operand.

Furthermore, the introduction of the set of buffer resources $\mathbb{R}_B$ implies that there are $\sigma^2(\mathbb{R}_B)$ transportation processes where the $\sigma()$ notation is introduced to give the size of a set. As a matter of convention, a healthcare process p_{Nu} transports a individual from resource $r_{y_1} \in \mathbb{R}_B$ to resource $r_{y_2} \in \mathbb{R}_B$ such that [7]–[12]. $u = \sigma(\mathbb{R}_B)(y_1 - 1) + y_2$.

Definition 13. Non-Transportation Process: A combination of non-transportation processes representing transformation, decision and measurement process, $p_B \in P_B$ that is a set union of non-transportation processes. $P_B = P_F \cup P_D \cup P_M$.

As many healthcare systems have hundreds or thousands of processes, it is often useful to form aggregated processes $\bar{\mathbb{P}}$. $\bar{P} = A_P \circledast P$, where $\circledast$ is an aggregation operator and A_P is an aggregation matrix. These aggregations are flexible and logical in nature. Since the healthcare sector has been so heavily influenced by fee-for-service reimbursement strategies, there have been many efforts to codify many of these services or processes to various degrees in various specialties.

In summary, the healthcare system processes are the set union of transformation, decision, measurement, and transportation processes. $P = P_F \cup P_D \cup P_M \cup P_N$

C. Healthcare System Concept (Knowledge Base)

Now that healthcare system function and form has been described, the allocation of their constituent processes to their associated resources can be presented. System concept is defined as an allocated architecture composed of a bipartite graph between the system processes and resources (shown as C in Figure 1). This is an integral aspect of many common engineering design methodologies [18], [25], [26]. Here, this work builds upon Axiomatic Design Theory, and more specifically for Large Flexible Engineering Systems [9], [27] where this allocation is mathematically formalized in terms of a "design equation" [7]–[12]. $P = J_S \odot \mathbb{R}$ where J_S is a binary matrix called a "system knowledge base" and $\odot$ is "matrix boolean multiplication" [7]–[12].

Definition 14. System Knowledge Base [7]–[12]: A binary matrix J_S of size $\sigma(P) \times \sigma(\mathbb{R})$ whose element $J_S(w, v) \in \{0, 1\}$ is equal to one when event $e_{wv} \in \mathcal{E}_S$ (in the discrete event systems sense [17]) exists as a system process $p_w \in P$ being executed by a resource $r_v \in \mathbb{R}$.

This system knowledge base definition has been applied to mass-customized production systems [7]–[12], transportation systems [28]–[30], water systems [9], [31], [32], and electric power systems [33] and is likely suitable to the healthcare delivery system as another instance of the class of large flexible engineering systems. It emphasizes the elemental capabilities that *exist* within the system.

It is important to note the healthcare delivery system knowledge base J_S has a special structure that can be determined from smaller knowledge bases that individually address transformation, decision, measurement, and transportation processes. Using the rules presented in Definition 8, it follows that:

$$P_F = J_F \odot \mathbb{R}_F \tag{4}$$

$$P_D = \begin{bmatrix} J_{FD} & J_D \end{bmatrix} \odot \left(\mathbb{R}_F \cup \mathbb{R}_D\right) \tag{5}$$

$$P_M = \begin{bmatrix} J_{FM} & J_{DM} & J_M \end{bmatrix} \odot \left(\mathbb{R}_F \cup \mathbb{R}_D \cup \mathbb{R}_M\right) \tag{6}$$

$$P_N = \begin{bmatrix} J_{FN} & J_{DN} & J_{MN} & J_N \end{bmatrix} \odot \left(\mathbb{R}_F \cup \mathbb{R}_D \cup \mathbb{R}_M \cup \mathbb{R}_N\right) \tag{7}$$

Consequently,

$$J_S = \begin{bmatrix} J_F & 0 & 0 & 0 \\ J_{FD} & J_D & 0 & 0 \\ J_{FM} & J_{DM} & J_M & 0 \\ J_{FN} & J_{DN} & J_{MN} & J_N \end{bmatrix} \tag{8}$$

The elemental capabilities that exist within the healthcare delivery system may not always be *available*. In the operational time frame, constraints may apply that effectively eliminate events from the event set. The existence of such constraints is captured within a system events constraints matrix.

Definition 15. System Events Constraints Matrix [7]–[12]: A binary matrix K_S of size $\sigma(P) \times \sigma(\mathbb{R})$ whose element $K_S(w, v) \in \{0, 1\}$ is equal to one when a constraint eliminates event e_{wv} from the event set.

Such constraints can be applied on technical resources in the form of breakdowns or maintenance. Similarly, human resources may call in sick or request other types of time off.

The construction of J_S and K_S allows the enumeration of the healthcare system's structural degrees of freedom.

Definition 16. Structural Degrees of Freedom [7]–[12]: The set of independent actions $\psi_i \in \mathcal{E}_S$ that completely defines the available processes in the system. Their number is given by:

$$DOF_S = \sigma(\mathcal{E}_S) = \sum_{w}^{\sigma(P)} \sum_{v}^{\sigma(\mathbb{R})} \left[J_S \ominus K_S\right](w, v) \tag{9}$$

where $\ominus$ is Boolean subtraction[1]. These structural degrees of freedom enumerate the capabilities of the healthcare delivery system independent of their sequence. They have been shown to be an essential step in determining the system behavior of several large flexible engineering systems including mass-customized production systems [7]–[12], transportation systems [28]–[30], water systems [9], [31], [32], and electric power systems [33].

D. Individual's 'Clinical' Health State Evolution

With the architecture of the healthcare delivery system in place, the discussion turns to an individual's health state evolution (shown as D in Figure 1). While it is important to quantify the capabilities of the healthcare delivery system, it is equally critical to introduce the evolution of each individual's health state so as to keep track of individual patient outcomes. Ultimately, this is necessary to meet the requirements presented in Table II so as to address healthcare delivery challenges posed by chronic conditions described in Table I.

It is here that the analogy between a personalized healthcare delivery system and mass-customized production systems firmly takes shape. In mass-customized production systems, each product is assumed to be entirely different from the one before it. For example, Mercedes Benz offered $3.347807348 \times 10^{24}$ variations on their Mercedes E class model in 2002 [34]. Human individuals are also unique. There exist a large number of unique operands that utilize different capabilities of their respective systems. Therefore, a systematic approach is required to model each individual.

In terms of modeling each individual, one must distinguish between the bio-physical-chemical *continuous* health state of the individual often found in systems biology [35] and an individual's clinical health state. The clinical health state is often ascertained by the clinician through differential diagnosis [36]. The process of diagnosis generally includes a form of *discrete* classification such as by: type (e.g. Type 1 diabetes), stage (e.g. Breast Cancer Stage IA), grade (e.g. Brain Tumor Grade II diffuse astrocytoma) or class (e.g. Heart Failure Functional Class I). Furthermore, the evolution of that state happens at irregular time intervals and often as a result of specific events be they from the healthcare delivery system (e.g. surgery), the environment (e.g. exposure to allergens), or new behavior (e.g. a new exercise regimen). Therefore, it is more appropriate to use a discrete event system model to describe the evolution of an individual's *clinical* health state.

To continue the analogy, in mass-customized production systems, the evolution of a product's state from raw good to finished product was described by a deterministic untimed Petri net called a "Product Net" [8]. Similarly, a "Health Net" is introduced, this time as a fuzzy timed Petri net, to model an individual's clinical health state.

Definition 17. Health Net: Given an individual l_i, that is part of a population L, where $L = \{l_1, ..., l_{\sigma(L)}\}$, the evolution of their clinical health state can be described as a fuzzy timed Petri-net [37]–[39]: $N_{l_i} = \{S_{l_i}, E_{l_i}, M_{l_i}, W_{l_i}, D_{l_i}, Q_{l_i}\}$, where:

- N_{l_i} is the health net.
- S_{l_i} is the set of places describing a set of health states.
- E_{l_i} is the set of transitions describing health events.
- $M_{l_i} \subseteq (S_{l_i} \times E_{l_i}) \cup (E_{l_i} \times S_{l_i})$ is the set of arcs describing the relations of (health states to health events) or (health events to health states).
- W_{l_i} is the set of weights on the arcs describing the health transition probabilities for the arcs.
- D_{l_i} is the set of transition durations.
- Q_{l_i} is the Petri-net marking representing the likely presence of the set of health states as a discrete probabilistic state.

The petri-net structure leads directly to the definition of its discrete-event dynamics.

Definition 18. Fuzzy Timed Petri Net (Discrete-Event) Dynamics [40]: Given a binary input firing vector $U^+[k]$ and a binary output firing vector $U^-[k]$ both of size $\sigma(\mathcal{E}_{l_i}) \times 1$, and the positive and negative components $\mathcal{M}^+_{l_i}$ and $\mathcal{M}^-_{l_i}$ of the petri-net incidence matrix of size $\sigma(S_{l_i}) \times \sigma(\mathcal{E}_{l_i})$, the evolution of the marking vector Q_{l_i} is given by the state transition function $\Phi(Q_{l_i}[k], U[k])$: $Q_{l_i}[k+1] = \Phi(Q_{l_i}[k], U^-[k], U^+[k])$, where $Q_{l_i} = [Q_{Sl_i}; Q_{\mathcal{E}l_i}]$ and

$$Q_{Sl_i}[k+1] = Q_{Sl_i}[k] \quad + \quad \mathcal{M}^+ U^+[k] \quad - \quad \mathcal{M}^- U^-[k] \tag{10}$$

$$Q_{\mathcal{E}l_i}[k+1] = Q_{\mathcal{E}l_i}[k] \quad - \quad U^+[k] \quad + \quad U^-[k] \tag{11}$$

Q_{Sl_i} is introduced to probabilistically mark Petri Net places where as $Q_{\mathcal{E}l_i}$ is introduced mark the likelihood that a timed transition is currently firing. The transitions are fired based on a scheduled event list that combines the discrete events with a time interval.

Definition 19. Scheduled Event List [17]: A tuple $\mathcal{S} = (u_\psi[k], t_k)$ consisting of all elements $u_\psi[k]$ in firing vectors

[1] $A \ominus B = A \cdot \bar{B}$. $A \cdot B$ is the Hadamadard product or equivalently matrix AND for Booleans. $\bar{B} = NOT(B)$.

$U^{-}[k]$ and their associated times t_k. For every element, $u_{\psi}^{-}[k] \in U^{-}[k]$, there exists another element $u_{\psi}^{+}[\kappa] \in U^{+}[\kappa]$ which occurs at time t_κ, d_ψ time units later. $t_\kappa = t_k + d_\psi$.

The health net is a practical representation of an individual's health state evolution from a clinical practitioner's perspective. Health states may include specific health factors (e.g. BMI level, glucose level) or may represent specific outcomes (e.g. pain level, cancer remission). The health events allow for the progression from one health state to the next as has been described in the scientific medical literature. The weights W_{l_i} on the arcs F_{l_i} are no longer integers but instead probabilities of 1.) a health state leading to a health event or 2.) a health event leading a health state. The introduction of event timing and fuzzy state evolution are now specifically included to account for the requirements presented in Table II.

An individual's health events E_{l_i} may be further classified. $E_{l_i} = E_{Fl_i} \cup E_{\varphi l_i}$. Each health event in E_{Fl_i} is triggered by the transformation processes P_F in the healthcare delivery system. Each health event in $E_{\varphi l_i}$ is the result of a stochastic human process P_φ. These stochastic human processes (i.e. the capability of the human body to change health state without a healthcare delivery system trigger) may occur randomly for unknown reasons or it may be mediated by non-healthcare delivery system factors that may be internal or external to the individual, such as: injury, social, economic, environmental, or biologic/genetic factors (e.g. car accident, BMI, gender). Note that in mass-customized productions systems $E_{\varphi l_i}$ do not exist. Furthermore, while the mass-customized production system describes a production transformation process (e.g. milling, painting) as having a single deterministic outcome, the scientific medical literature describes healthcare transformation processes (e.g. cancer therapy) as having several probabilistic health outcomes (e.g. cancer recurrent or cancer in remission) which would be reflected in the partially marked state Q_{l_i}.

Finally, in mass-customized production systems the product net had events that occurred instantaneously. In contrast, the health net has events with stochastic duration. This is particularly important as an individual's health recovers and degrades at different rates.

With the Health Net model in place, it becomes important to understand how the full evolution of the clinical health states can be partitioned into *episodes*.

Definition 20. Episode: a partition of the health net $N_{\mathcal{E}l_i} = \{S_{\mathcal{E}l_i}, E_{\mathcal{E}l_i}, M_{\mathcal{E}l_i}, W_{\mathcal{E}l_i}, Q_{\mathcal{E}l_i}\} \subset N_{l_i}$ describing a single noteworthy happening characterized by an underlying condition be it acute or chronic.

The set of episodes are assumed to be collectively exhaustive of the health net. $N_{l_i} = \bigcup_j N_{\mathcal{E}_j l_i}$. Furthermore, with respect to health events, episodes are mutually exclusive; $\bigcap_j E_{\mathcal{E}_j l_i} = \varnothing$.

The definition of health nets and episodes allows a return to the central premise of the paper summarized in Tables I and II. More specifically, episodes can be classified as either *Acute* or *Chronic*.

Definition 21. Acute Condition: occurs as an episode (e.g. infection, trauma, fracture) with a short clinical course that usually responds to treatment where a return to a state of complete-pre-morbid health is the rule [41].

This definition facilitates two assumptions. 1.) Acute conditions are mutually exclusive. $\bigcap_j N_{\mathcal{A}_j l_i} = \varnothing$, which implies that for n acute conditions

$$M_{l_i} = \begin{bmatrix} M_{A_1 l_i} & 0 & 0 \\ 0 & \ddots & 0 \\ 0 & 0 & M_{A_n l_i} \end{bmatrix} \tag{12}$$

2.) The duration of an acute episode occurs on the order of a duration of a facility visit. This explains why the primary focus of many works on discrete event simulation in the healthcare delivery system literature [13] is on minimizing transportation and wait times.

Definition 22. Chronic Condition: occur as episodes (e.g. diabetes mellitus, cancer) that have a protracted, usually more than 6 months clinical course, requiring long-term therapy where response is suboptimal and return to a state of complete or pre-morbid normalcy is the exception [41].

Consequently, and unlike acute conditions, chronic conditions are not mutually exclusive. $\bigcap_j N_{C_j l_i} = \varnothing$. Furthermore, the duration of a chronic episode is much longer than a duration of a facility visit, and therefore health events may occur both inside and outside the clinic.

In summary, it is important to recognize that the health net fulfills three of the requirements in Table II. It specifically understands the clinical health state and tracks it as individuals reach favorable health outcomes. Finally, it recognizes that health events can be part of chronic episodes that are of long duration that can occur well after the individual has left the healthcare facility.

E. Linking Healthcare System State with Individual Health State

In order to link the transformation processes of the Healthcare Delivery System to the Individual Clinical Health State Evolution, a coordination link is necessary (shown as E in Figure 1).

In mass-customized production systems the linking between the production system state and the product state is captured using the product transformational feasibility matrix [7]–[12], where each transformation process in the production system induces a product event. Analogously, each transformation process in the healthcare delivery system induces its corresponding health event. For each individual, l_i, this feasibility condition can be captured in a binary individual transformational feasibility matrix.

Definition 23. Individual Transformation Feasibility Matrix Λ_{F_i} [7]–[12]: a binary matrix of size $\sigma(E_{l_i}) \times \sigma(P_F)$, where $\Lambda_{F_i}(x, j) = 1$ if transformational process p_{F_j} realizes the health event e_{xl_i}.

Since each transformation process realizes exactly one individual health event, the sum of each column of the individual transformational feasibility matrix must equal one. The sum of

TABLE III
SUMMARY OF THE PERSONALIZED HEALTHCARE DELIVERY SYSTEM

(A) System Form Resources	buffer(R_B)[transformation(R_F) ∪ decision(R_D) ∪ measurement(R_M)] ∪ transportation(R_N)
Resource Classification	transform>decide>measure>transportation
(B) System Function Processes	transformation(P_F) ∪ decision(P_D) ∪ measurement(P_M) ∪ transportation(P_N)
(C) System Context	
System Knowledge Base	$J_S = \begin{bmatrix} J_F & 0 & 0 & 0 \\ J_{FD} & J_D & 0 & 0 \\ J_{FM} & J_{DM} & J_M & 0 \\ J_{FN} & J_{DN} & J_{MN} & J_N \end{bmatrix}$
System Constraint Matrix	$K_S = \begin{bmatrix} K_F & 0 & 0 & 0 \\ K_{FD} & K_D & 0 & 0 \\ K_{FM} & K_{DM} & K_M & 0 \\ K_{FN} & K_{DN} & K_{MN} & K_N \end{bmatrix}$
Structural Degrees of Freedom	$DOF_S = \sum_w^{\sigma(P)} \sum_v^{\sigma(\mathbb{R})} \left[J_S \ominus K_S\right](w, v)$
(D) OPERAND	**HEALTH NET**(N_{l_i})
places	health state(S_{l_i})
transitions	health event(E_{l_i})
transition duration	fixed duration(D_{l_i})
arc weight	Stochastic ('Fuzzy')(W_{l_i})
(E) COORDINATION	**HEATHCARE**
Operand Transformation	Individual Transformation Feasibility Matrix(Λ_{F_i}) of size $\sigma(E_{l_i}) \times \sigma(P_F)$

each row gives the number of times that each transformation process is required by the individual.

Note that in mass-customized production systems, there are typically more unique transformation processes then in all the mass-customized products being produced [42]. In contrast, the healthcare delivery system typically only has transformation processes if they serve to improve individuals' health state. Meanwhile, all the health events in $E_{\varphi l_i} \forall l_i$ are entirely autonomous of the healthcare delivery system.

This section presented a personalized healthcare delivery system model following the conceptual depiction in Figure 1. The personalized healthcare delivery system is summarized in Table III following the nomenclature of the conceptual depiction in Figure 1.

III. DISCUSSION & CONCLUSION

The strengths of the model arise from several network structures that allow for coordinated healthcare while distinguishing between acute and chronic conditions. They are: the aggregation matrices A_R and A_P, the system knowledge base J_S, the system events constraints matrix K_S and the health net N_{l_i}. Together, these structures serve to provide appropriate, coordinated, and personalized healthcare to unique individuals. Furthermore, each of these matrices may be viewed as the outcome of a healthcare delivery system design decision. These decisions are now discussed in the context of the five parts of the healthcare system architecture shown in Figure 1.

The aggregation matrices A_R and A_P were introduced to view the Healthcare Delivery System *Form & Function* at higher levels of aggregation. The need for physical aggregation reflects how teams of healthcare professionals and groups of technical equipment must often be brought together to form a single operating unit (e.g. surgical team in an operating theatre). Similarly, the need for functional aggregation reflects how many low level system processes are required to perform a single healthcare service (e.g. perform orthopedic surgery).

The system knowledge base J_S was introduced to view the Healthcare Delivery System *Concept* in terms of the *existence* of capabilities that are the feasible combinations of system processes and resources. It is a succinct description of what the system can do and how. In hiring new personnel or procurement of new technical equipment, new columns are added to J_S. When new personnel represent new specializations, new rows are added J_S. Training programs allow each human resource the ability to execute new system processes.

The system events constraints matrix K_S was introduced to the Healthcare Delivery System *Concept* to distinguish between the existence and the *availability* of capabilities. Some availability constraints are planned. These include shift changes for human resources and planned maintenance for technical resources. Other constraints may be viewed as unplanned disturbances to the architecture. They include personal and sick leave for human resources and breakdowns for technical resources.

The health net N_{l_i} for a given individual l_i was introduced as a mathematical description of clinical science where the individual's health state requires coordination with the healthcare delivery system to achieve the desired health outcomes. In the healthcare of acute conditions, where the timescale is relatively short, health events driven by stochastic human processes $E_{\varphi l_i}$ may not have the chance to occur and so it is reasonable to assume that the health evolution of an individual is purely determined by the health events driven by healthcare transformation processes E_{Fl_i}. In such a way an individual (patient) becomes a passive entity in the healthcare delivery system. Such is the inherent assumption of many works on discrete event simulation of medical emergency healthcare operations [43], [44]. In contrast, in the healthcare of chronic conditions the health events driven by stochastic human processes $E_{\varphi l_i}$ play a prominent role and it becomes important to track the evolution of an individual's health state as had been done in mass-customized production systems [45].

That said, an individual's health state has several features that distinguish it from mass-customized products. First, the state of the mass-customized product is typically completely understood and quantifiable, whereas the true state of the human being's health is typically fuzzy. Consequently, the healthcare delivery must heavily utilize measurement processes to ascertain this state; the fundamental reason for the inclusion of measurement processes in the process classification. Second, individuals (or patients) may be viewed as semi-autonomous decision-making rather than passive entities [24]. In that regard, the intelligent (mass-customized) product literature [20], [21] may prove a relevant extension of the analogy presented in this paper. Recent work has specifically included a product net at the heart of an intelligent product agent's data structure [11] and so one can expect the health net to take a similar role for individuals. As a third distinguishing feature, this model specifically includes decision capabilities because individuals often need to physically meet with clinicians in order for these shared decisions to occur [24].

In conclusion, this paper architects a system model for personalized healthcare delivery and managed individual health outcomes. This work is built upon analogous mass-customized production systems.It highlights the stochastic evolution of an individual's health state as a key distinguishing feature. In so doing, it systematically addressed the new healthcare delivery system requirements described in Table II that were derived from healthcare delivery challenges posed by chronic conditions described in Table I.

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