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Turbulence in Production Systems – Fluid Dynamics and its Contributions to Production Theory

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***Abstract*— Future production systems need to cope with a high degree of flexibility in terms of fluctuation of demand, product variants, etc. without loosing sight of an increasing cost pressure. For the resolution of this dilemma this work focuses on the adaption of basic principles of similitude and fluid dynamics to production theory in order to increase the production velocity while avoiding regions of instability, or turbulence, at the same time. Subsequently, an experimental setup for the verification of this analogy model is developed and discussed.**

***Index Terms* — Production Theory, Fluid Dynamics, Turbulence, Modeling.**

I. INTRODUCTION

Today, industrial companies are challenged by a highly dynamic environment, which compels them to develop and manufacture products at a high level of flexibility and quality at low costs. [1] The fast and global transfer of information and open markets are, besides the economic aspects, the main drivers of changing the global structure of manufacturing. [2]

Considering industrial production in high-wage countries today, these trends can be cut down on two dilemmas that are closely related to each other (see Figure 1). [3] The first dilemma refers to the "value-oriented vs. planning-oriented" production. The former approach (value orientation) focuses on value adding processes without the consideration of planning-, preparation-, handling- and transport processes whilst the latter focuses on extensive planning in order to optimize value-adding (i.e. modeling, simulation, information gathering, etc.).

The second dilemma is related to the "scale-scope" dimension. Either the production system is designed for high scale output without variances in the product design (critical masses, business and manufacturing process decomposition, mastered processes) or it is designed for individual products down to a production batch of a unique product, i.e. complex and highly integrated processes. The resolution of this production-related polylemma is the main target of the Cluster of Excellence "Integrative Production Technology for High Wage Countries" (see Figure 1).

Especially the scale-scope dilemma is boosted by global trends like mass customization and open innovation which result in a highly fluctuating demand for individualized products at costs matching or beating those of mass production.

II. PRODUCTION SYSTEM FOR HIGH-WAGE COUNTRIES

To achieve a sustainable competitive advantage for production in high-wage countries, it is not sufficient to reach a better position within one of the dichotomies "scale-scope" and "planning-orientation vs. value- orientation". The research question must aim at the resolution of both dichotomies, the polylemma of production, see Figure 1. This means that, in addition to the maximisation of the share of added-value activities without neglecting the planning quality and optimisation, economies of scale and economies of scope have to be maximised at the same time.

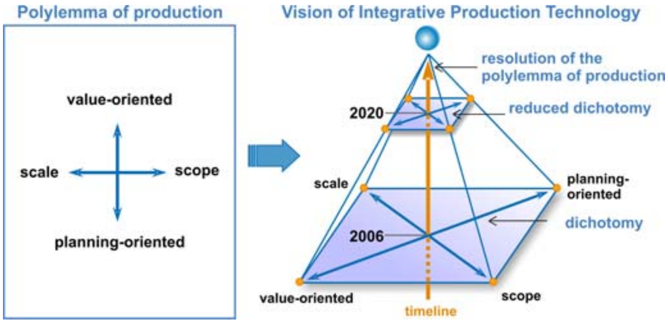

Figure 1: The polylemma of production

Individualised production is defined as a concept for designing and aligning all the elements of a production system in a way which enables a high level of product variety and dynamics whilst maintaining manufacturing costs matching or beating those of mass production. Product programme and architecture, production processes and resource structure are the key elements within the production system. The one-piece-flow represents the ideal state in which products are customised or developed and manufactured individually (lot size one), and flow constantly throughout the product creation chain as single units. In order to realise a one-piece-flow, the design, realisation and production have to contribute to a minimization of set-up efforts.

The key for the resolution of the globally boosted scale-scope dilemma is the development of a configuration logic that enables the optimal design of production systems.

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In this case optimality refers to the dynamic allocation of all elements of a production system along the value chain to enable the production of customer specific goods at costs of mass production. [4] Against this background several questions have to be answered. Considering the lot size, one question will be for example: Is it possible to enlarge an economically optimal operating point (lot size) of production systems into an optimal operating range (lot size range)?

Hence, this research contributes to the resolution of the dichotomy between scale and scope by enabling production systems to cope with higher product diversity and dynamics by realising one-piece-flow throughout the whole production system.

The key to reach this target is the adaption of the overall design of the production system. A production system is the combination of all elements (product programme, product architecture, production processes, and resource structure, see Figure 2) needed for the economic design of value chains for the creation of products and their variants. Yet, state-of-the-art production systems are not capable of ensuring the economic optimum (i.e. optimum operating range) since they focus only on single elements of the entire production system (either product or production related focus) [6]. Therefore, the main research question is:

How can the economically optimal operating point of production systems be widened to an optimum (product variants dependant) operating range to produce individualised products at costs matching or beating those of mass production?

III. CONFIGURATION LOGIC FOR PRODUCTION SYSTEMS

Theoretically, the answer of this research question is the holistic consideration and alignment of all relevant elements and their attributes that enable a production system to be able to produce individualised products at costs of mass production. The elements of a production system are highly interdependent and interconnected by “spring-damper units” (design fields in Figure 2). Thus, the production system shows an emergent characteristic (i.e. principle of irreducibility). However, the elements of this system are planned and operated in an individual way [7]. Against this background a logic for the configuration of a production system will be developed that comprises theses interdependencies.

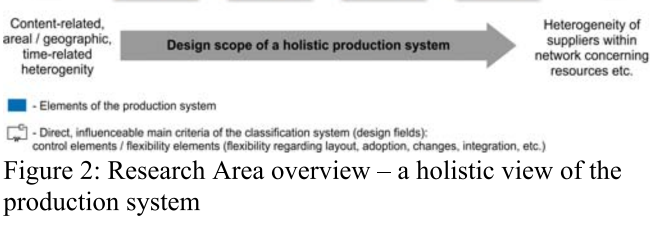


Figure 2: Research Area overview – a holistic view of the production system

The configuration logic will suggest an adequate set up of the production system to enhance the reduction of the scale-scope dilemma. To define the logic for the configuration, the interdependencies between production systems’ elements have to be revealed. Wiendahl for example identified the basic relation between logistic performance indicators like lead-time or adherence to delivery dates in respect to the stock of inventory. [8] Against this background the lead time will increase by increasing the stock of inventory.

Certain principles or phenomena can be identified by observation. Little’s law, for instance, tells us that the long-term average number of customers in a queue in front of a bank counter for example is equal to the long-term average arrival rate multiplied by the long-term average time a customer spends at the bank counter. [9]

In natural sciences general principles or phenomena can be validated by experiments. An experiment is a test under controlled conditions. While certain phenomena in natural science can be tested under controlled conditions, the behaviour of a production system is too unmanageable to ensure the requirements of controlled conditions. Therefore other methods have to be chosen to validate observations within the world of production systems.

The next chapter will describe and motivate the basic ideas for the revelation of the interdependencies between elements of the production system by simulating chosen elements and deriving principles for the production systems by the adaption of the basic principles of fluid dynamics and similitude theory.

IV. TURBULENCE-OPTIMIZED PRODUCTION SYSTEMS

As described above, future production systems need to cope with a high degree of flexibility in terms of fluctuation of demand, product variants, etc. without loosing sight of an increasing cost pressure. This dilemma generates an unprecedented degree of complexity which makes it inevitable to change the point of view from a static to a dynamic one. [10] However, production systems are characterized by a static view of organizational, technical and economical attributes [11], which makes it impossible to quantify neither the quality nor the flexibility of such a system over time.

In science it is quite common to look for “best practices” in other fields of research in order to find analogies that are able to describe and explain a certain phenomenon. Considering the case of production systems, several attempts have been made, e.g. adopting the viable systems model [12] to analyze the integrity of production systems. [13] This paper describes the characterization of production systems by means of applying the laws of fluid dynamics and similitude theory to a “production flow”. Although the application of fluid dynamics in the area of production is not quite new, for instance Kachani et al. deployed this approach in transport and pricing, [14] the application of fluid mechanics for the modelling of dynamic or even chaotic effects in production systems can not be found in literature yet.

A. *Fluid mechanics – Basic principles*

For the description of the flow of a fluid (particle) through a continuum three equations are necessary. The first equation describes the conservation of mass, the second equation describes the conservation of momentum and the third equation describes the conservation of energy. Usually, these equations are addressed as “Navier-Stokes equations”. Considering an incompressible flow, i.e. ρ = constant, and thus the decoupling of the energy, momentum and conservation of mass equations, the Navier-Stokes equations can be written as: [15]

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + \nu \nabla^2 u_i + F_i$$

$$\frac{\partial u_i}{\partial x_i} = 0 \tag{1}$$

with:
u_j = velocity in j direction
F_i = body forces per unit mass
ρ = density
The Laplace operator is written as

$$\nabla^2 = \frac{\partial^2}{\partial x} + \frac{\partial^2}{\partial y} + \frac{\partial^2}{\partial z} \tag{2}$$

By these equations, incompressible fluids, i.e. the behaviour of (arbitrary) particles (dependant on time and space) in a fluid, are mathematically completely described.

B. *Similitude Theory*

Yet, even with the simplifications of an incompressible flow it is usually not possible to solve the equations analytically and to determine all the essential facts for a given fluid (flow) by pure theory. Hence, dependence must often be placed upon experimental investigations. The number of tests to be made can be greatly reduced by a systematic program based on dimensional analysis and specifically on the laws of similitude or similarity, which permit the application of certain relations by which test data can be applied to other cases. Thus the similarity laws enable the development of experiments with a convenient fluid such as water or air, for example, and the application of the results to a fluid which is less convenient to work with, such as gas, steam or oil. Additionally, valuable results can be obtained at minimum costs by tests made with small-scale models of the full-sized apparatus. The first step in applying the similitude theory to real-life problems is the formation of a dimensionless problem. By using the following scales and non-dimensional variables:

$$x_i^* = \frac{x_i}{L},\quad t^* = \frac{tU_0}{L},\quad u_i^* = \frac{u_i}{U_0},\quad p^* = \frac{p}{p_0},\quad \frac{\partial}{\partial x_i} = \frac{1}{L}\frac{\partial}{\partial x_i},\quad \frac{\partial}{\partial t} = \frac{U_0}{L}\frac{\partial}{\partial t^*} \tag{3}$$

Where * signifies a non-dimensional variable the non-dimensional Navier-Stokes equations can be written as follows

$$\frac{U_0^2}{L}\cdot\frac{\partial u_i^*}{\partial t^*} + \frac{U_0^2}{L} u_j^* \frac{\partial u_i^*}{\partial x_j^*} = -\frac{p}{\rho L}\frac{\partial p^*}{\partial x_i^*} + \frac{\nu U_0}{L^2}\frac{\partial^2 u_i^*}{\partial x_j^* \partial x_{ji}^*}$$

$$\frac{U_0}{L}\cdot\frac{\partial u_i^*}{\partial x_i^*} = 0 \tag{4}$$

The length and velocity scales have to be chosen appropriately from the problem under investigation, so that they represent typical lengths and velocities present (see Figure 3)

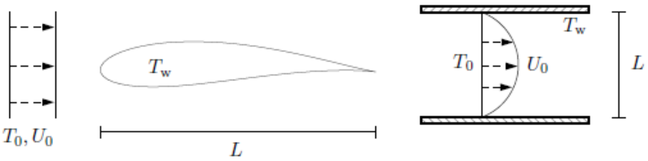


Figure 3: Examples of length, velocity and temperature scales

By dropping * as a sign of non-dimensional variables and dividing through with U_0^2 /L one obtain

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\frac{p_0}{\rho U_0^2}\frac{\partial p}{\partial x_i} + \frac{\nu}{U_0 L}\nabla^2 u_i$$

$$\frac{\partial u_i}{\partial x_i} = 0 \tag{5}$$

The last term of conservation of momentum defines the Reynolds number Re

$$\mathrm{Re} = \frac{U_0 L}{\nu} \tag{6}$$

which can be interpreted as a measure of the inertial forces divided by the viscous forces. The Reynolds number is by far the single most important non-dimensional number in fluid mechanics.

C. *Fluid mechanics in production theory – An analogy model*

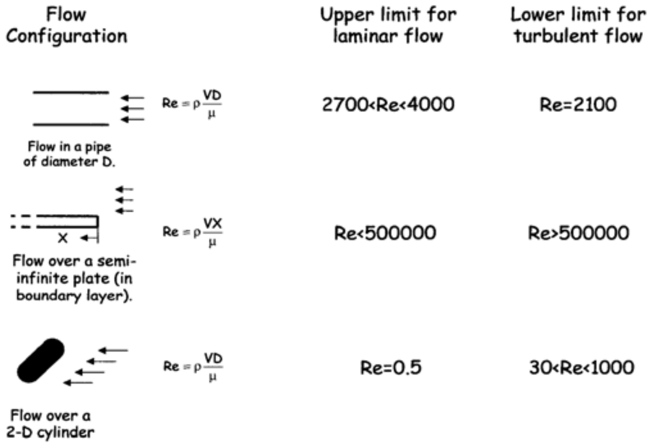
The most important application of the Reynolds number is the interpretation of a flow in terms turbulence. For low values of Re the flow is laminar and ordered. Within a certain range of values for Re there exists a region of gradual transition where the flow is neither fully laminar nor fully turbulent, and thus fluid behavior can be difficult to predict. As a general rule, there is a threshold — often indicated by a critical Reynolds number ($\mathrm{Re}_{\mathrm{crit}}$) — that conventionally separates the laminar from the turbulent zone. For higher Re values the flow becomes turbulent. For example, within circular pipes the $\mathrm{Re}_{\mathrm{crit}}$ is generally accepted to be around 2.300. Since this number is not a strict limit value, engineers will avoid any pipe configuration that falls within the range of Re from about 2.000 to 4.000 to ensure that the flow is either laminar or turbulent. [16]

Since production systems can be interpreted as the means through which materials and information flow, the fluid dynamics explanation of the flow can be adapted to the production context in search for an enlightenment of the relations between lead time, performance, production structure and the configuration of the production system.

The term L in the Reynolds number refers to the physical structure of the means through which the fluid flows. It can be related to the pipe section area, its shape, surface roughness, and all aspects that either facilitate or complicate the regular, laminar flow. From a production point of view L can be associated to structural complexity dimensions. In fact, literature provides evidence that, for a given product and speed required by the customer, the coordination of logistics flows becomes more and more complicated — and, at the end, turbulent or chaotic — when vertical, horizontal, spatial and relational complexities increase. [17] Hence, production system complexity dimensions (i.e. the L term in the Reynolds number) either facilitate or complicate the flow. In terms of production systems L can, for example, refer to the number of machining or mounting stations, to the number of products, variants and so on.

The kinematic viscosity ν in the Reynolds number characterizes the fluid flowing through a certain environment, e.g. a tube. The viscosity depends on the viscous interactions within the flow of the particles. Strong interactions in viscous fluids facilitate the regular flow even at high velocities. The properties of a fluid flowing through a pipe network can be associated to the characteristics of products flowing through the production system. The characteristics of products are connected to the processes that companies configure to manufacture, distribute and retail the products. [17] By introducing the dynamic viscosity $\mu = \nu \cdot \rho$, this dependence can be modeled by the density ρ, which can be interpreted as those product/process characteristics that can complicate the (managerial) task of laminar activity flows at high velocities (e.g. overall dimensions, weight, fragility and volume). Since the viscosity μ indicates the strength of interaction between the fluid particles, it can be associated with those product/process characteristics that determine the required level of coupling between the activities in the process, e.g. non commutative processes like roughing and finishing.

The velocity term in the Reynolds number (U_0) can be interpreted as the velocity of flows through the production system which is, in other words, the reciprocal ratio of the lead time. Striving to continually increase the rapidity of the production system without changing its structure, the business process configuration can cause a risky drift towards chaos. By increasing the velocity while maintaining the other factors (i.e. viscosity and characteristic length) the Reynolds number rises and thus pushes the flow towards turbulence. With regard to the actual values of such Reynolds numbers it is important to take into consideration that the values greatly depend on the geometric setup, i.e. the architecture of the production system (see Figure 4). For instance, the limit for a turbulent flow over a semi-infinite boundary plate can be found in the range of $Re \approx 50.000$. [18] This has to be kept in mind when applying the Reynolds number to production systems since most production systems are nor alike. Consequently, the boundary conditions play an important role for deciding whether a flow through a production system is laminar or turbulent.



Flow Configuration		Upper limit for laminar flow	Lower limit for turbulent flow
Flow in a pipe of diameter D.	$Re = \rho \frac{VD}{\mu}$	2700<Re<4000	Re=2100
Flow over a semi-infinite plate (in boundary layer).	$Re = \rho \frac{VX}{\mu}$	Re<500000	Re>500000
Flow over a 2-D cylinder	$Re = \rho \frac{VD}{\mu}$	Re=0.5	30<Re<1000

Figure 4: Limits for laminar and turbulent flows for different configurations

In order to come to better understanding of the Reynolds number in production systems in analogy to fluid dynamics, experiments have to be set up in order to identify regions of turbulent and laminar flow. Since most real life production systems are not accessible, a system according to [19] has been set up at the “Lernfabrik” at RWTH Aachen University. In order to assure a maximum flexibility in the experimental setup the production system and its constraints (which can be adopted) were implemented into a commercial software tool (Plant Simulation). The schematic representation of the production is depicted in Figure 6.

Due to this flexibility, it is possible to adjust (almost) all factors of the production system that may influence the Reynolds number, i.e. the production system structural complexity dimensions (e.g. number of machines, manufacturing time, rejections, etc.), the characteristics of products (e.g. lot size, etc.) and the velocity. Whereas the former expressions refer to what is generally described as boundary conditions of a production system, the velocity (the reciprocal ratio of lead time, see above) usually is to be optimized in order to satisfy the demand for minimized costs of working capital, short customer response times, etc. Unfortunately, these optimization approaches can result in a turbulent flow which is no longer predictable and thus controllable.

Hence, the aim of this investigation is to identify regions where the velocity can be increased without reaching areas of non-controllable turbulence by introducing a certain margin of dynamic rigidity. Such a Reynolds-optimised production system fulfils both, the augmented demand for decreased lead times and the structural stability to cope with a highly fluctuating demand at the same time.

In order to investigate the behaviour of the depicted system and to identify certain areas of turbulence where the production system is no longer controllable the basic setup of the simulative experiment is kept fix while some of boundary conditions (e.g. lot size, etc.) are changed. The result of the experiment is a change in the lead time (as a measure for the velocity, see above) which consequently effects the Reynolds number of the depicted production system. The experimental setup is discussed in detail in the following chapter.

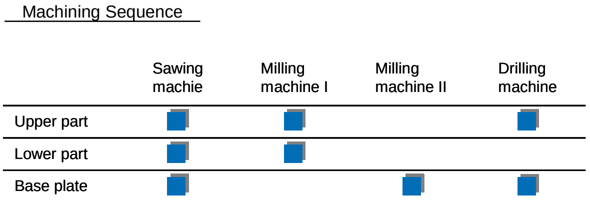
V. EXPERIMENTAL SETUP

The experiment is carried out using the commercial simulation software Plant Simulation by Siemens UGS. This software helps to create digital models of logistic systems (e.g. production) to explore the systems' characteristics and to optimize its performance. By using a digital model, an experiment can be carried out without installing the real system. [20] This software offers a graphical user interface as well as a programming front end to customize the digital model. A library of system elements offers already defined production machines with the opportunity to determine process or setting-up time.

For the experiment, a virtual copy of a production system is needed. Because of the complexity, the first experiments will only focus on the production process. The following paragraph describes the CUBE Corporation, [19] a fictional company, which determines all relevant parameters for the simulation.

The CUBE Corporation produces cubes for the toy industry. A cube consists of three parts: an upper part, a lower part and a base plate. All parts can be manufactured out of the same raw material. Every week the supplier delivers the necessary amount of raw material to the company. The amount of raw material can be calculated based on the weekly production volume. The production program for each day can be determined for each experiment. For the first experiments the CUBE Company produces just one variant of the cube. In later experiments the number of cubes and variants will rise in order to compare the results.

The production process of the cubes consists of several machines, assembly stations and a testing station. For each production step several characteristics can be defined: e.g. processing time [s], setting time [s], availability [%], lot size [#], rejections [%] or reconditioning [%]. One possible machining sequence is depicted in Figure 5. The machining sequence of the parts is variable and can be adapted, too. Even the number of lots within a sequence can be defined for each experiment.



	Sawing machie	Milling machine I	Milling machine II	Drilling machine
Upper part	■	■		■
Lower part	■	■		
Base plate	■		■	■

Figure 5: Machining sequence

After the manufacturing of the parts, the upper and lower part are assembled and tested. After positive testing, the base plate is attached to the assembly and the production process finishes (q.v. Figure 6). Before each single production step an interim stock will collect the individual parts until the defined lot size has been reached. The size as well as the basic setting of each stock is adjustable. After the defined lot size has been reached, the next process step will start. For the production control either push or pull principle can be used. Push control necessitates a detail planning for every production step (e.g. sequence of machining). Pull control will decentralize the planning. In this case, each production step "asks" individually for the necessary amount of parts autonomously. The successor production step defines the right amount of parts needed for the predecessor production step. In this case no detailed planning for each production step and day is needed.

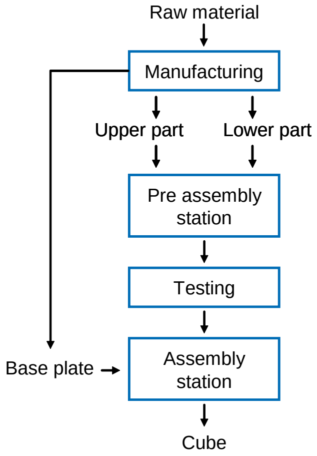


Figure 6: Cube production process

During the simulation the program records e.g. the amount of parts within each interim stock, the holding time for each part, the amount of finished cubes and the lead time of a cube. By changing the input parameters (e.g. lot size, processing time etc.) the lead time (for example) will change as well. The development of the interim stock may give a hint why the lead time changes and explain the change.

The input parameters will be changed ceteris paribus to compare the different experimental results and to ensure a controlled condition. While Wiendahl revealed the interdependencies for different logistic performance indicators for just one product, it would be interesting to reveal those interdependencies for a multi product production system.

VI. CONCLUSION AND OUTLOOK

Future production systems need to cope with a high degree of flexibility in terms of fluctuation of demand, product variants etc. without loosing sight of an increasing cost pressure. This dilemma generates an unprecedented degree of complexity which makes it inevitable to change the point of view from a static to a dynamic one. However, production systems are characterized by a static view of organizational, technical and economical attributes. This makes it impossible to quantify neither the quality nor the flexibility of such a system over time.

This work focuses on the adaption of basic principles of fluid dynamics and similitude theory to production theory. Discussions about fluid dynamics are often connected to laminar or turbulent flows throughout a pipeline or other networks and thus inevitably connected to the Reynolds number. Concerning the "conventional" Reynolds number, which describes the ratio of the initial and viscous forces in an arbitrary fluid, a production related analogy is developed in order to identify regions where non-controllable turbulent flows may occur. These regions consequently have to be avoided when optimizing the production velocity, i.e. reducing the lead time, since the production system is no longer controllable within those regions. By contrast, in areas of confidence, i.e. regions of laminar flow, the lead time can be reduced to the maximum possible extend. Hence, these Reynolds-optimized production systems can cope with a high degree of volatility in terms of demand, lot size, etc. while maintaining minimized lead times at the same time.

Because it is not possible to conduct an experiment with a real-life production system, a software simulation is set up to identify basic interdependencies of production system elements and to formulate principles for production systems in general by using the analogy of fluid dynamics and similitude theory. The simulation comprises a fictional company, the CUBE Corporation, and its virtual production system. By changing certain characteristics (e.g. lot size, processing time etc.) the change in lead time (for example) can be recorded. By analyzing the stock gradient or the holding time, changes in the lead time may be explainable.

Future work has to focus on the explanation of the experimental results. Furthermore the experimental setup needs to be adapted and extended in order to translate the findings of the experiments to other production systems. Striving for possible (universally valid) solutions, the first step is to identify the predominating variables of production systems in general. In analogy to the similitude theory, these variables enable the dynamic evaluation and comparison of different systems by means of dimensionless key ratios, like for example the Reynolds, Mach or Euler number. In order to find these predominating variables (or *dimensions*) in analogy to the principles of physics, different experimental setups has to be varied widely and compared with real life systems which is the next step in future work.

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