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Stability of balancing competing demands: A network flow analysis with process control

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ABSTRACT

The purpose of this thesis is to investigate the dilemma of competing demands through the perspective of process control. The allocation of competing demands is modeled across three fluid flow systems of varying sizes and degrees of control. The control gain (Kc) represents the intensity and valence of demand for resource. A higher Kc correlates to a more urgent demand. The integral time (τ_i) represents the time between demands. A low τ_i correlates to a quick and high frequency demand. Relationships between these control parameters were applied to the concept of competing demands. Here the thesis discovered that beyond maintaining correlated values within a given systems stability threshold, values must respect a given systems maximum or minimum tolerance of process variable, or resource, quantity. For control to be properly applied to a process of competing demands a combination of value of Kc and τ_i must be able to bring the process to a desired set point without hurting the process's efficiency or security. Further, for process control itself to be effective it must respond and stabilize with a quickness required by the system. It was found that a system of more controls will allow for a greater range of stability parameters but increase the maximum flow value for those given parameters. Yet the thesis presents a set of rules and trends to follow when applying process control, maximization of success for applied process control must be system and scenario dependent.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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Chapter 1 : Introduction

The issue of competing demands confronts the proper allocation of a limited resource between multiple entities requiring more resource than available. Here a limited resource can be anything of value of a scarce quantity. Limited resources can be money, time, labor, inventory, goods and so on. Whether consciously or not, everyone faces the issue of competing demands on a nearly daily basis. For example, a student faces this dilemma when choosing how to properly divide their resource of time between schoolwork and extracurricular activities. More specifically let's say each afternoon a student has homework and wants to go to gym. The student has a limited resource of 5 hours and homework and the gym request 4 and 2 hours respectively. Deciding how to allocate their time is an issue of competing demands. In making a proper decision there are demand factors of urgency and frequency, and situational definitions of an ideally balanced outcome.[1]

The demand factor of urgency or intensity can also be described by the psychologic theory of valence, the level of attractiveness or repulsion to a situation. Specifically, the intensity of demand can be treated as an absolute value of its valence.[2] The demand factor of frequency is simply seen as how quickly and often the request is made. Inherently, a demand of both high intensity and frequency is more likely to get a larger portion of the limited resource than a demand of both low intensity and frequency.

Going back to the student example, let's say the homework is only a small portion of the courses total grade, here this may cause the demand to be a low intensity. Maybe despite the low intensity, the student is doing very poorly in the class and is very anxious about the homework. This anxiety could result in a high frequency of demand. Similar evaluations could be made for the demand to go to the gym. A high standard for fitness could equate to high intensity but tiredness could cause low demand frequency. The student's decision to allocate time in an afternoon is best viewed as subjective to the specific scenario and student.

Factors of demands can more concretely be expressed in the following scenario. Here a company has a limited budget that supplies department A, manufacturing, and department B, research and development. Each department independently contacts the manufacturer with funding requests. Here the intensity of demand is seen by how urgently the funding is requested. The frequency of demand is seen by how quickly and often the department discusses and reminds the company of their request. In all competing demand dilemmas, it is crucial that the intensity and frequency of requests does not cause an unbalance in the system. An unbalance begins when department A makes a demand with an intensity and/or frequency too high for the system. Here in response to their demand, department A gets swift funding and quickly reaches their desired amount. However, because of the intensity and frequency of their demand the company is sending more funding their way which will greatly exceed the desires of department A. Without knowing of these incoming funds and seeing success in their last demand, department A continues to make funding demands at this level. This now leaves department B with an unexpected low and decreasing amount of funds. Here department B panics and increases their demand intensity and frequency to compete with that of department A's. If department B's new demand is strong enough the allocation of funding will shift away from department A and cause them to further increase their demand factors. Here an escalating tug-of-war has begun over a limited resource that will result in an increasing fluctuation of the allocation of funds and an overall unbalance. When a system becomes unbalanced, resource demands are crafted to compete rather than meet realistic needs.[3]

Yet an unbalanced scenario of competing demands is quite apparent, defining and reaching the best balance is more subjective. When facing the dilemma of competing demands an ideal allocation of resources will vary system-by-system. Rather than attempt to define the best balance of competing demands this thesis will offer a new perspective and set of tools for processes to tackle this issue. Through the lens of a fluid flow system undergoing process control, this thesis will strive to answer,

How can varying levels of control and control parameters (Kc and τ_i*) be utilized to best allocate competing demands for a given process system?*

Chapter 2 : Background

Piping Network Analysis

Piping network analysis (PNA) is a hydraulic study of a fluid flow system. Over the years many approaches have been developed to investigate and simulate piping systems of various sizes and complexities. Most approaches are based on conversion of mass,

$$\sum Q_{in} - \sum Q_{out} = 0 \qquad (1)$$

where [Q] is the volumetric flow rate of a constant and incompressible fluid, and an energy balance,

$$\sum h_L = 0 \qquad (2)$$

where [h_L] is head loss of each pipe. It is often desired that a piping PNA is solved through a series of equations, varying by the system size.[4]

Bernoulli and Flow

The Bernoulli equation is one of the most common tools in analyzing fluid flow and can be most vaguely defined as a conservation of potential and kinetic energies between two points in fluid flow.

$$\Delta \mathrm{P} + \frac{1}{2}\rho\Delta v^2 + \rho g\Delta \mathrm{z} = \mathrm{F} \qquad (3)$$

Here change in pressure (ΔP), change in velocity (Δv), and change in height (Δz) compares the conditions of two distinct points in a “balanced” fluid flow. The density (ρ) and specific gravity (g) of the fluid are treated as constants. The friction head (F) is the change in pressure caused by the resistance on fluid by the system. Friction head is defined by,

$$F = f\frac{L}{r}\rho v^2 \qquad (4)$$

Here the length (L) and radius (r) of the pipe are constant. The friction factor (f) is calculated based on the flow type, laminar or turbulent.[5]

Turbulent flow occurs when flow is relatively faster to the extent where the fluid undergoes a random, chaotic, mixing motion through the system. Laminar flow occurs more commonly at relatively lower flow rates. In laminar flow, the fluid travels uniformly without mixing along the diameter of the system. In laminar flow surface friction of the system causes a parabolic shape of flow where more central fluids have a higher flowrate than outer fluids. Mathematically, turbulent and laminar flow is determined by the calculation of the unitless Reynolds number (Re). Where fluid viscosity is given by [u].

$$Re = \frac{2rv\rho}{\mu} \qquad (5)$$

In general, a Reynolds number above 2,100 is indictive of turbulent flow, whereas a Reynolds number below 2,100 corresponds to laminar flow. [5]

The friction factor (f) may then be calculated based on flow type,

Laminar (Re < 2,100): $$f = \frac{16}{Re} = \frac{8\mu}{r\rho v} \qquad (6)$$

Turbulent (Re > 2,100): $$f = 0.0791 \left[\frac{\mu}{2r\rho v} \right]^{\frac{1}{4}} \qquad (7)$$

Process Control

Process control is an application of adaption to variability in a system so that a desired output can be maintained. This desired output is treated as the set-point (SP). The variable of the desired, set-point, outcome is referred to as the process variable (PV) and what is changed to reach this result is referred to as the manipulated variable (MV). A change in the manipulated variable will result in the change of the process variable. The ratio of these change is the process gain (Kp), [6]

$$Kp = \frac{\Delta \mathrm{PV}}{\Delta \mathrm{MV}} \qquad (8)$$

The time it takes for the process variable to respond to the change manipulated variable is known as the dead process time (θp). If the response is instantaneous the dead process time is 0, but cannot be negative. The controller receives an error (E) from the system defined as the difference between the set-point and the process variable.

$$E = SP - PV \qquad (9)$$

Controller output (C) is the signal sent from the controller back to the system, telling the system how to respond to reach the set-point. The sensitivity of the control output in relation to the error is based on the controller gain (Kc), not to be confused with process gain.[6]

The most common form of process control systems follows the PID (proportional, integral, derivative) algorithm. This thesis will focus on the application of a PI (proportional, integral) feedback control.[7]

In proportional only control, the control output is exactly proportional to the received error.

$$C = Kc\, E + C_o \qquad (10)$$

The bias term (C_o) is utilized so that controller output is not zero with a zero-value error and is especially important in proportional only control. As proportional only control output changes only with change in control error, there will always exist an offset between the set-point and the process variable. Increase in Kc reduces this offset in trade for system stability.[6]

This offset can be mitigated by the addition of an integral term for process control,

$$C = \frac{Kc}{\tau_i} \int E \;\; dt \qquad (11)$$

Also given by,

$$C = \frac{Kc}{\tau_i} \sum(E)\, ts \qquad (12)$$

Here the integral time (reset time) (τ_i) is the time between each repeat, adjusted to control the impact of the integral term. The time step (ts) is the amount of time allotted between each error reading in the sum. The integral term considers past error and is utilized to eliminate the offset a proportional only control.[6,7]

The combination of proportional and integral terms (PI control) results in,

$$C = C_o + Kc\, E + \frac{Kc}{\tau_i} \int E\, dt \qquad (13)$$

Or,

$$C = C_o + Kc\, E + \frac{Kc}{\tau_i}\sum(E)\, ts \qquad (14)$$

Process control may also utilize a derivative term to account for future change.

$$C = Kc\, \tau_d \frac{dE}{dt} \qquad (15)$$

Here derivative time (τ_d) is used to control the impact of the derivative term.[6] While the addition of a derivative term improves the process control, in many cases it is unnecessary. Simple PI control is far more common, approximately 90% of controllers, as it is substantial in control and easier to tune and optimize.[7]

Competing Demands

The concept of competing demands, also referred to as an organizational paradox, investigates issues of managing a valued resource under limited quantity.[8] The competing demands occurs in the situation in which a resource of value is being required at a greater quantity than available. The issue of this scenario arises in the proper allocation of the limited resource among the demanding sources. There are many courses to approach an issue of competing demands and the result of the issue often looks different based on your approach's perspective. To address competing demands separately or simultaneously, short or long-term, aggressively or subtly, as an outlier or as part of a system, will result in different evaluation and allocation of resource. The ideal solution to any dilemma of competing demands is dependent on the surrounding environment and system which the demands take place.[1]

The Beer Distribution Game

The "Beer Distribution Game," created by MIT's Dr. Jay Forrester in the 1950s, simulates the roles of stages in the production and distribution of consumer goods. The game is carried out as a four-stage supply chain of the retailer, wholesaler, distributor, and manufacturer. The typical result of the game is a phenomenon known most commonly as the bull whip effect. The bull whip effect refers to the amplifications of oscillations of inventory observed across the stages of the process. The bull whip effect is felt more severely the further upstream the stage despite downstream stages being more responsible.[9] An unstable supply chain that struggles with the bullwhip effect is incredibly inefficient. Such a supply chain will often suffer from excess spending on inventory, consistent shut downs, product shortages and an overall highly fluctuating work environment.[10] Yet the beer distribution game does not utilize a control system, a successful supply chain requires control to mitigate the bull whip effect.

Similar Research

Previous studies have approached supply change, a topic of resource management and flow that often faces the issue of competing demands, through applications of fluid flow and process control. Yet while this thesis does not build off this research, it serves as successful application of flow and control principles to the allocation of resources at varying scales and settings.

In his 2009 study, Romano analyzed the supply chain and resource management of the casual wear industry through the scope of fluid dynamics. The allocation of resource of this incredibility fast pace industry is not only increasing in complexity but has expanded across the world. To allot for the tight margins for timing error Romano analyzed distribution structures through the perspective of fluid flow. Laminar flows below a critical speed allowed the distribution to function properly, whereas a turbulent flow above a critical speed would have a detrimental impact on the supply chain flow despite the face value, higher speed.[11]**Error! Reference source not found.** Under this system an industry wide scale issue of competing demands could be better gauged to how to respond to fluctuations in demand and scope of product at the time of order. This perspective investigated a large scope of supply chain at an industry size.[12]

Studies have analyzed managing resources by PID control focused on the inventory level of each step entity. PID control managing step inventory as a tank level provides specific, adaptive and predictive decision-making analysis that can be addressed at an in depth, stage specific, basis. This perspective takes a closer look at supply chain management at ground level with the potential to build up. Here is a smaller scale analysis of product flow.[13,14]

Chapter 3 : Hypothesis

Concept

The idea of this thesis is to display and investigate the allocation of valued resource among competing demands through a fluid flow system. The allocation of competing demands will then be accessed in the scope of process control. In this representation, the limited resource is represented by the fluid in the system. All fluid flow within the system is treated as laminar. This fluid is distributed from one source (inlet) to multiple demands (outlets). This distribution occurs through a system of purely piping. There is no capacity beyond the piping within the system, or in other words, there is no storage of resources in the system. Rather, the system's storage of resources is to be treated as a distinct outlet stream.

Conservation of mass creates the executive balance for modeling this system. Here the total flow entering the system is equal to sum of flow exiting the system. There is no flow (resource) generated or stored (lost) in the system,

$$\sum Q_{in} - \sum Q_{out} = 0 \tag{16}$$

Governing values of the system are the piping parameters of length and radius, and the inlet and outlet pressures. The piping lengths (L) and radii (r), along with the fluid viscosity (μ), are used to calculate the resistance of a given pipe,

$$R = \frac{8\mu L}{\pi r^4} \tag{17}$$

This resistance, along with change in pressure along a pipe (ΔP) is used to calculate flow,

$$Q = \frac{\Delta \mathrm{P}}{\mathrm{R}} \tag{18}$$

Resistance of each pipe is utilized as the manipulated variable, a change in pipe resistance will be carried out through process control to bring the a given pipe's flow (Q), the process variable, to the desired set point. The change in pressure depicts the initial demand of the resource. The flow inlet will have a pressure that correlates to the initial quantity of limited resource flow. A higher pressure will result to more flow. The outlet pressures correlate to the initial demand of the resource to the given outlet. A lower pressure will result in a greater initial pull for the resource.

The system undergoes PI process control. A desired outlet flow rate (SP) deviating from the initial flow rate from system conditions is applied. This demanded desired flow rate will have two parameters. Control gain (Kc) will correlate to the severity of the demand. Increasing Kc will be equivalent to increasing urgency for fluid flow. The integral time (τ_i) will represent the time interval in which the demand in repeated. τ_i is equivalent to the time between each demand. A low τ_i is equivalent to a quick and frequent reminder of demand. A model of the control process applied to the fluid flow system is provided in **Appendix A**, **Figure 13**.

Control Parameters

Increase in Kc increases the controller output response to any given error. Decrease in τ_i increases the controller output response to any given error. In the case of a change in SP increasing Kc and/or decreasing τ_i causes the process variable to both reach the SP faster and overshoot the SP by a larger magnitude. Here oscillations around SP will increase in frequency. For an infinitely small Kc or an infinitely large τ_i there will be no overshoot and the desired SP will never be completely reached.[6,7]

Kc and τ_i must be adjusted collaboratively to avoid maximum and minimum values of oscillations that will disrupt the system and cause it to run inefficiently or insecurely. These peak and trough values are dependent on system conditions.

All systems undergoing control can experience severe consequence if the magnitude exceeds a system dependent point. Let's say the process variable is a manufactured product, toilet paper. Here there exists a maximum amount of toilet paper that a single manufacturing plant can produce. If set point, desired toilet paper production, increases under control parameters too heavily favored towards a fast response a toilet paper production oscillation of too high magnitude will follow. If the peak is too high, above the point of possible production, then the plant may go into unneeded overtime, overwork machinery, drop customers, short production of other items made in the plant, or invest to expand the plant. More simplistically, there exists a peak point where a process can no longer run efficiently or securely. Following the peak is the trough. Here there is another point in which production too low causes severe consequence. There will now be too little production for the plant to work efficiently. Further a high magnitude trough can leave the manufacturer vulnerable to unexpected surges in demand where it would not easily be able to compete. Just as with the peak, there exists a bottom point where a process can no longer run efficiently or securely.

Kc and τ_i must be adjusted collaboratively so that a system reaches a new SP within a given, system and scenario dependent, stability time. The stability time is how long it takes for process control to reach a point where all values of the process variable are within a stability tolerance of the SP. Here stability tolerance is a system and scenario dependent fraction of the SP. Once the process variable remains within the stability tolerance of a SP the process can be deemed stabilized.[7]

With all other parameters set, a systems ideal Kc and τ_i is to be dependent on a balance between the process's tolerance to overshoot and speed required to reach the new SP. This balance exists within the parameter barriers that would produce a stable control.

A stable control is one which the process variable (Q) converges to the set point. A stable process control is not automatically successful.

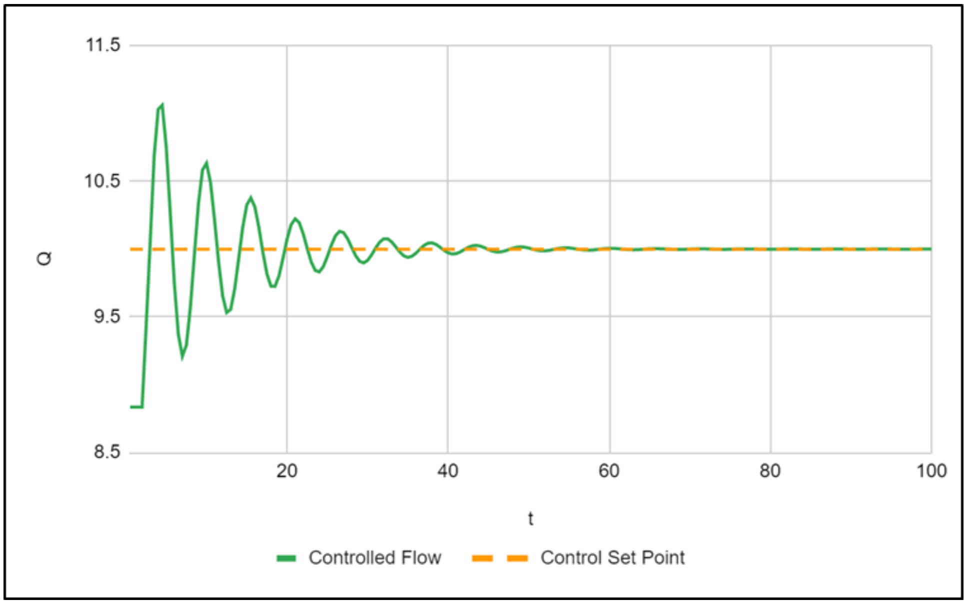

Figure 1 - Stable Control

An unstable control is one which the process variable does not converge to the SP. When a system is unstable the magnitude of process variable oscillations will increase with time. An unstable control is one which the Kc is too high for the given τ_i and/or system conditions. This control scenario results from misapplied process control in which the process controller itself causes the system to lose control.

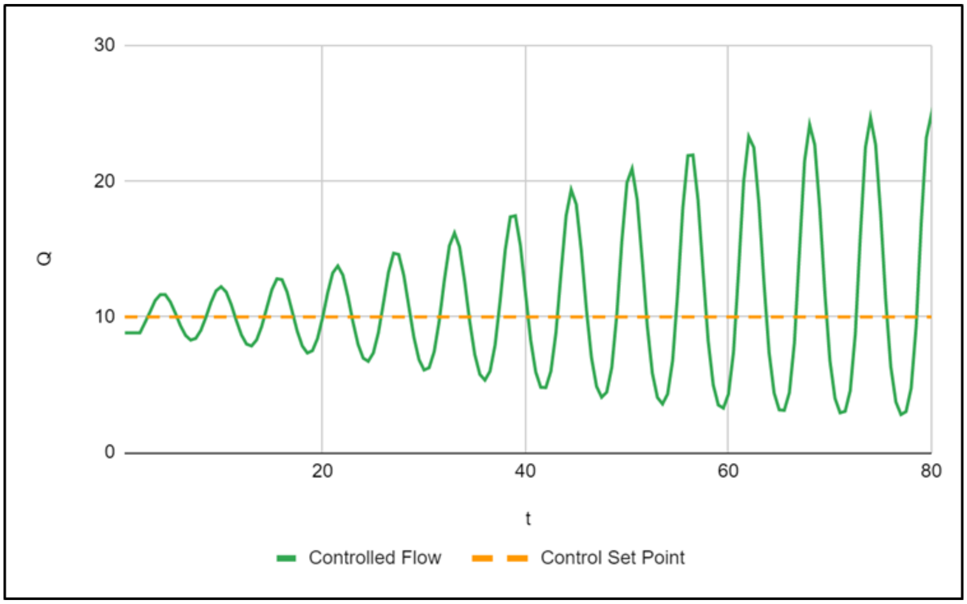

Figure 2 - Unstable Control.

For any given systems conditions and τ_i there exists a maximum Kc where control is on the brink of instability. A ringing control or a control at the stability threshold depicts a system right before becoming unstable. Here the magnitude of oscillations is consistent and neither decreasing, stabilizing, or increasing, destabilizing.

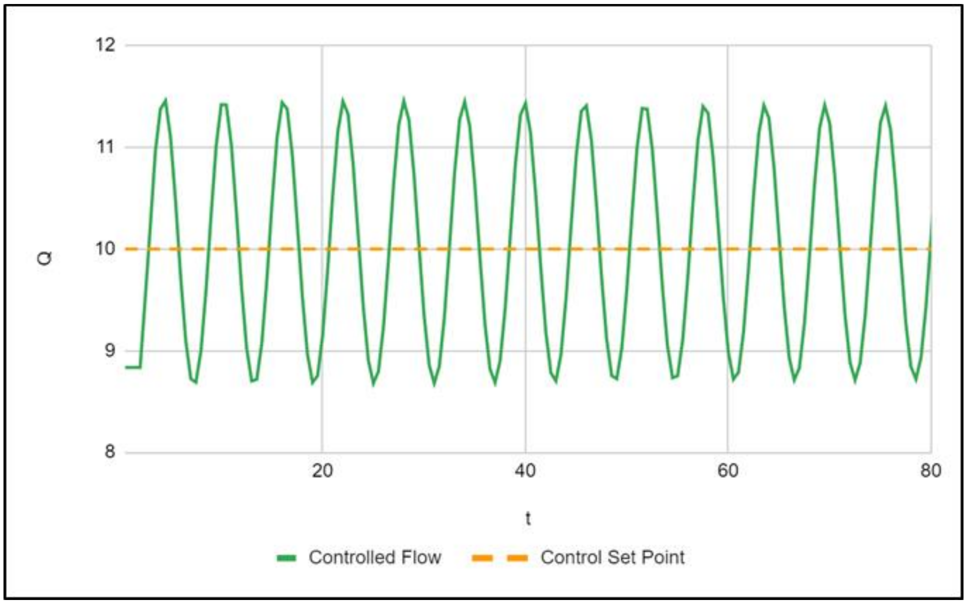

Figure 3 - Ringing/Stability Threshold

A graphical representation of Kc's relationship with τ_i at a systems stability threshold would provide an area which all combinations of parameters within would result in a stable control. Based on control parameters change's influence on process variable such a graphic would have increasing stability area as τ_i increases. Here the most stable control system consists of a high τ_i and low Kc. Considering the stability threshold, the end point of a stabilizing control system, a lower τ_i will be least stable and require a lower Kc to maintain stability. As τ_i increases the system becomes more stable, allowing for an increase in Kc while maintaining stability. The relationship between the two control parameters is not linear and an infinitely large τ_i will not allow for an infinitely large Kc. For any given process there will be a maximum Kc the system can withstand before becoming unstable. As τ_i approaches infinity the Kc stability threshold will approach this maximum value. This relationship between τ_i and Kc is consistent among systems of varying conditions, size, controls, and SPs.[6,7]

Chapter 4 : Test Method

Model

This thesis utilizes three distinct excel/google doc models of fluid flow systems undergoing process control. Each system consists of one inlet whose flow is split into varying outlets with one or two controllers. For each system there is no capacity besides piping volume. Fluid is treated as room temperature water, with viscosity (μ) of 0.001 kg/m sec, and density (ρ) of 1,000 kg/m^3.

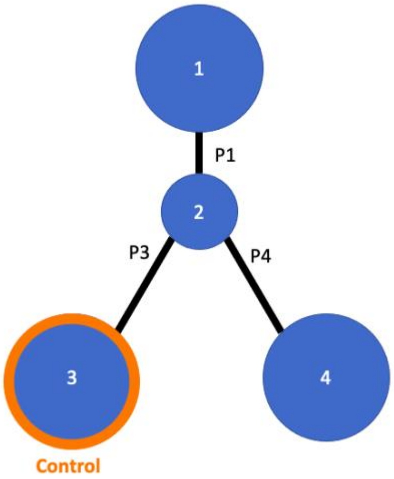

Figure 4 - System 1

One inlet flow. Two outlet flows, one of which is controlled.

The first, **System 1** consists of points 1,2, 3, and 4. Point 1 being flow inlet, 2 being where the flow splits, and 3 and 4 being flow outlets. 1p, 2p, and 3p are pipes with given lengths (L) and radius (r) used to calculate resistance of the pipe (R):

$$R = \frac{8\mu L}{\pi r^4} \tag{19}$$

The fluid flow (Q) of each pipe can be represented by:

`

$$Q = \frac{\Delta P}{R} \tag{20}$$

Where ΔP is the change in pressure from inlet to outlet of each pipe.

As there is no additional capacity besides the pipes, **System 1** follows the simple mass balance:

$$Q1 - Q3 - Q4 = 0 \tag{21}$$

Or,

$$\frac{\Delta \mathrm{P1}}{\mathrm{R1}} - \frac{\Delta \mathrm{P3}}{\mathrm{R3}} - \frac{\Delta \mathrm{P4}}{\mathrm{R4}} = 0 \tag{22}$$

The changes in pressure can be written in two ways,

$$\Delta \mathrm{P1} + \Delta \mathrm{P3} = \mathrm{P1} - \mathrm{P3} \tag{23}$$

$$\Delta \mathrm{P1} + \Delta \mathrm{P4} = \mathrm{P1} - \mathrm{P4} \tag{24}$$

Solving for ΔPs results the following system of equations,

$$\Delta \mathrm{P1} = \frac{[(\mathrm{P1}-\mathrm{P3})\ \mathrm{R1\ R4}+(\mathrm{p1}-\mathrm{P4})\ \mathrm{R1\ R3}]}{[\mathrm{R1\ R4}+\mathrm{R1\ R3}+\mathrm{R3\ R4}]} \tag{25}$$

$$\Delta \mathrm{P3} = \mathrm{P1} - \mathrm{P4} - \Delta \mathrm{P1} \tag{26}$$

$$\Delta \mathrm{P4} = \mathrm{P1} - \mathrm{P3} - \Delta \mathrm{P1} \tag{27}$$

This finalizes the system of equations that creates the base model of the **System 1** given, inlet and outlet pressures and piping parameters.

System 1 has a process controller around outlet point 3. Here a controller gain (Kc), integral time (τ_i), dead time (θp), time step (ts), and set point (SP3) is given. For utilization throughout this thesis, θp and ts are held constant. It is notable that θp and τ_i values are converted to steps. Controller output (C) is then calculated using equation 14 and a C_o of zero. C impacts R, as it directly correlates to the pipe flow. R is adjusted each step [n].

$$R_n = R_{n-1}(1 + C_{n-1}) \tag{28}$$

At any given ts, the model provides ΔP, R, Q, SP, proportional E, integral E, and C values. These results are based on the system conditions of L, r, P, Kc, τ_i, θp, ts, and SP held constant per trial.

Systems

As stated above, **System 1** consists of the fluid flow model of inlet stream split into two outlets and one outlet undergoing process control, **Figure 4**.

Two additional systems, **System 2** and **System 3**, are referenced throughout the thesis. Both **System 2** and **System 3** consist of a fluid flow model of one inlet stream split into three outlets. Here the series of equations is expanded for the additional outlet, but calculated by the same process. **System 2** utilizes one process control around a single outlet (Q3). **System 3** utilizes two process controls each around an individual outlet (Q3 and Q4). For simplicity, in **System 3** both process controls have equal control parameters, Kc, τ_i, θp, ts, and SP.

All three systems have the same initial piping parameters and outlet pressures. The inlet pressure (P1) vary between **System 1** and both **System 2** and **System 3**, as to maintain consistent initial inlet flow (Q1) among all three systems. All details system parameters kept constant throughout thesis are documented in **Appendix B**.

Chapter 5 : Results and Discussion

Set Point Impact

When the desired outcome (SP) of a controlled demand is equal to the initial outcome based on system conditions (P, L, a), there is no change in system flows. There will be no change of flow until there is a change in system conditions or desired outcome.

Increase in the desired outcome of a controlled demand (SP3) will equally increase the demand outcome (Q3), assuming control is stable. Increase to match desired outcome will result in an increase in input (Q1) and a decrease in uncontrolled outcome (Q4). An increase in resource demand by controlled output pulls from both input and uncontrolled output.

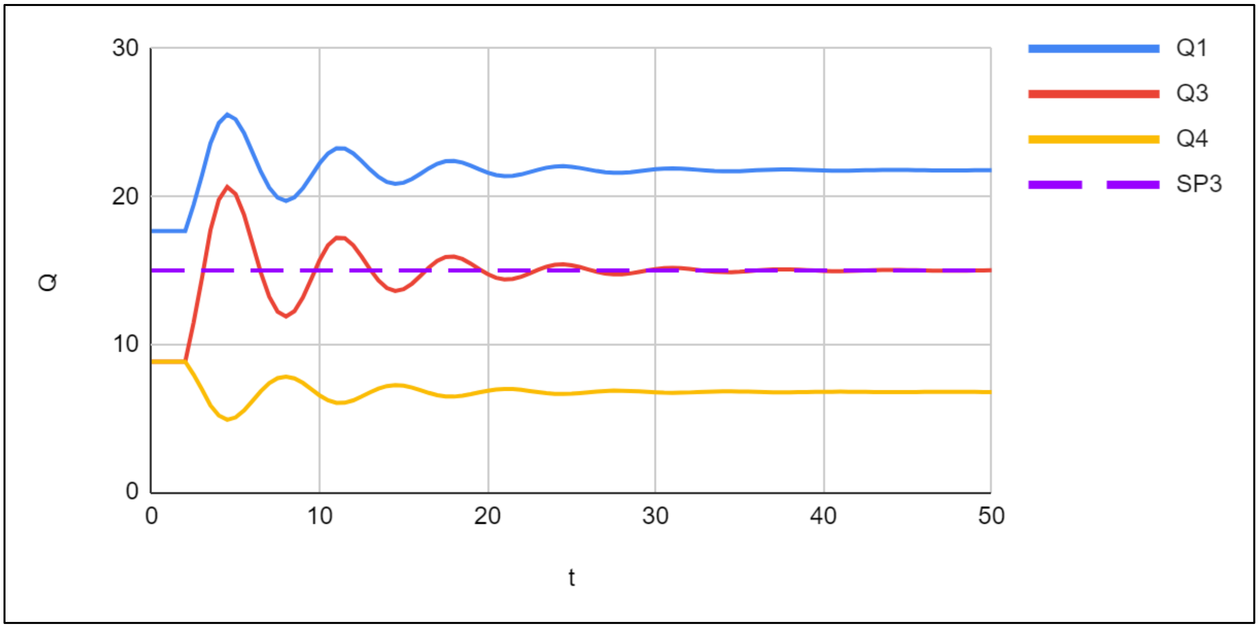

Figure 5 - Increase in Set Point: System 1 initial outlet flow (Q3) of 8.8 raised to 15, resulting in increase of inlet flow (Q1) and decrease of uncontrolled outlet flow (Q4).

Similarly, decrease in the desired outcome of a controlled demand (SP3) will equally decrease the demand outcome (Q3), assuming control is stable. Decrease to match desired outcome will result in a decrease in input (Q1) and an increase in uncontrolled outcome (Q4). A decrease in resource demand by controlled reduces input and pushes resource to uncontrolled output.

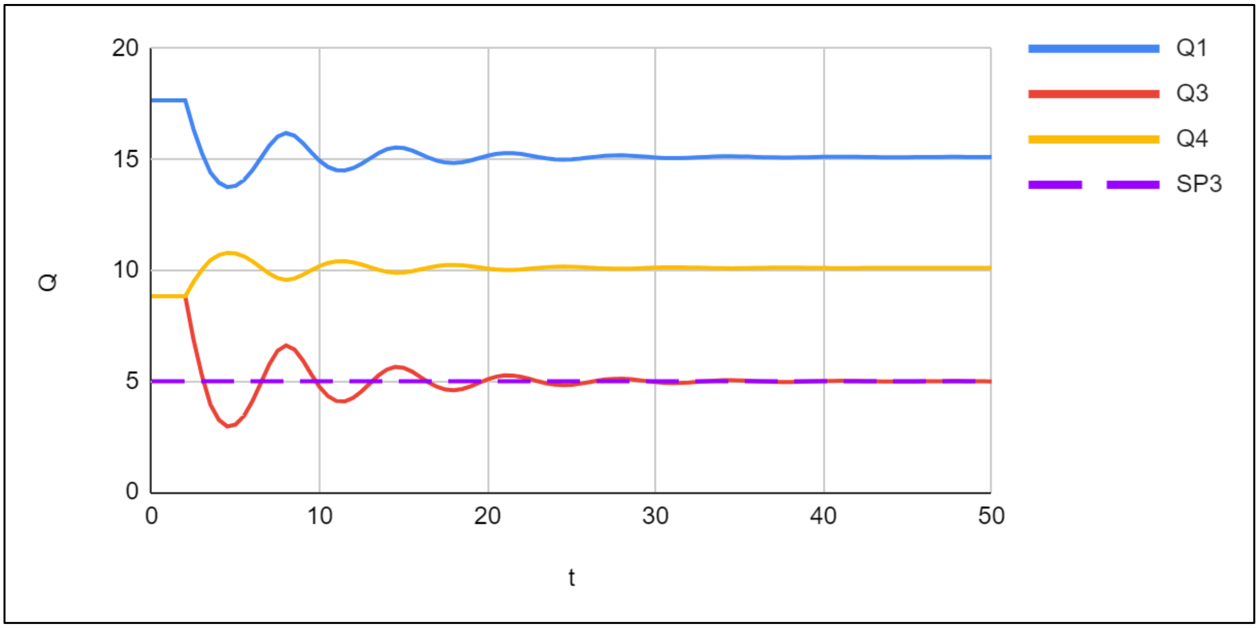

Figure 6 - Decrease in Set Point: System 1 initial outlet flow 8.8 reduced to 5, resulting in decrease of inlet flow (Q1) and increase of uncontrolled outlet flow (Q4).

By observation of the three systems utilized in this thesis, the input and output response to an increase or decrease in set point is consistent among varying control conditions. The variation of set point from initial control stream output, the ratio of resulting change in input and uncontrolled outputs to change in controlled stream is consistent for given system conditions.

For System 1, with set system conditions of **Appendix B**, the change in input (Q1) and uncontrolled output (Q4) are 2/3 and 1/3 the change in controlled output (Q3), respectively. These ratios of change are constant for the given set system conditions (L, r, P) despite changes in control parameters (Kc, τ_i, SP). This suggests that for a process of known system parameters held constant, the resulting change in uncontrolled point of the process can be calculated based on desired change in controlled point. Here, for a well known process, the impact of the adjustment of a control set point should be able to be calculated beforehand, assuming stability. This relationship can then be utilized to indirectly control points of a process that don’t have a literal process control applied to them.

Effective Control within Stability

Stable controls of process variable Q with varying values of Kc and τ_i are depicted below.

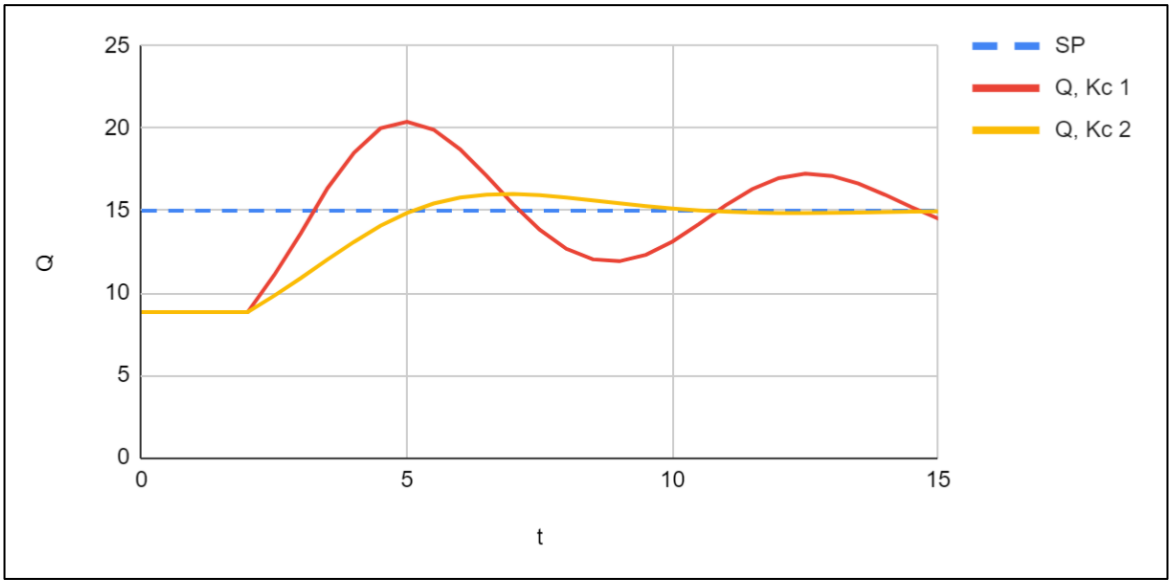

Figure 7 - Kc 1 > Kc 2: System 1, Kc 1 = - 0.005, Kc 2 = - 0.002, τi = 0.1. Larger Kc results in PV reaching SP faster but overshooting SP by higher magnitude.

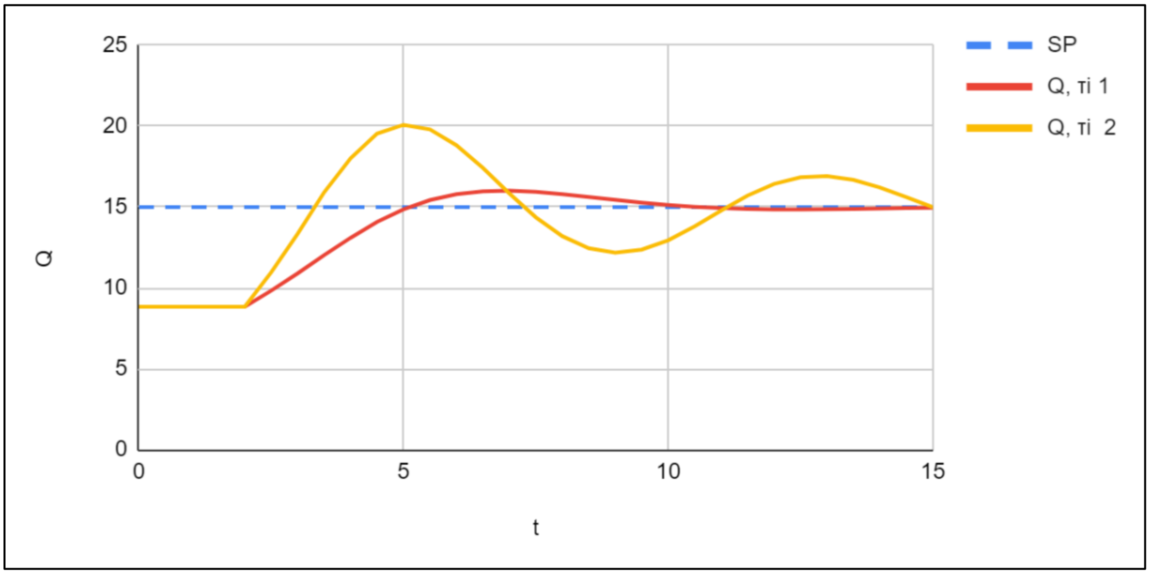

Figure 8 - τi 1 > τi 2: System 1, τi 1 = 0.1, τi 2 = 0.05 , Kc = - 0.002. Smaller τi results in PV reaching SP faster but overshooting SP by higher magnitude.

As stated previously and illustrated above, a controlled system has a better response to change with larger Kc and/or smaller τ_i. On the other hand, this increase in Kc and/or decrease in τ_i increases magnitude of oscillations. It is essential that the system is able to withstand the magnitude of the peaks and troughs of oscillation.

Despite stable control, parameters of Kc and τ_i must be adjusted collaboratively to avoid magnitudes of oscillations that will disrupt the system and cause it to run inefficiently or insecurely. For any given system conditions, the maximum and minimum values of resulting control oscillations can be calculated to properly select parameters of Kc and τ_i.

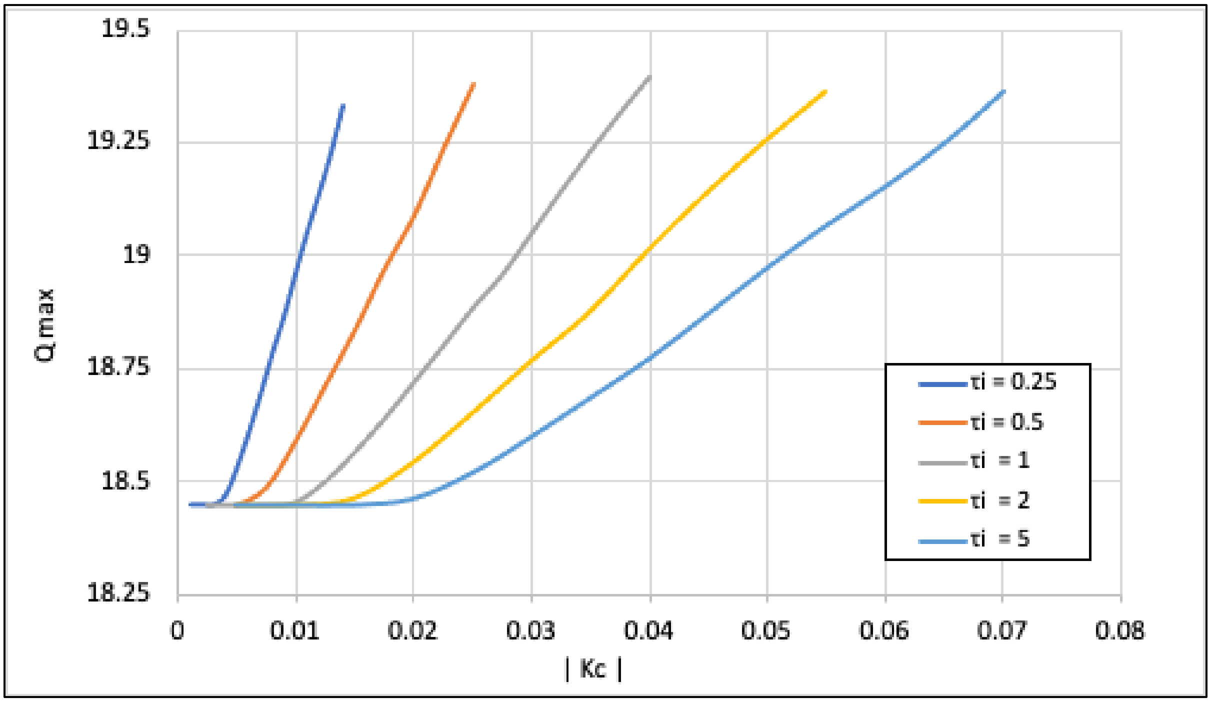

Figure 9 - Maximum Flow produced by given Kc and τi: System 1. The process must be capable of handling corresponding maximum PV to apply values of Kc and τi. Q max scale here does not begin at 0.

Above depicts the control parameters in correlation to maximum inlet flow for system 1. It is seen that lower integral time results in max flow being very sensitive to increases in control gain. It is important to keep in mind a figure such as this doesn't illustrate the benefit of control response. As seen in **Appendix D**, max flow data for systems 2 and 3, the relationship between max flow and control parameters is consistent among system orientations. Here multiple controllers in a system result in an increase in max flow. This relationship will later be seen as a trade off with increased stability with more controllers.

Here, a process of competing demands relies on an appropriate balance on urgency (Kc) and frequency ($1/\tau_i$) of demands for both the process and control to maintain effectiveness.

Control Stability

A crucial aspect of a process control is that it is not misapplied, driving the system itself to lose control. As illustrated in **Figure 3** for any given system conditions there exists a set of Kc and τ_i that results in oscillation ringing. This scenario is the stability threshold, the brink of a system losing control.

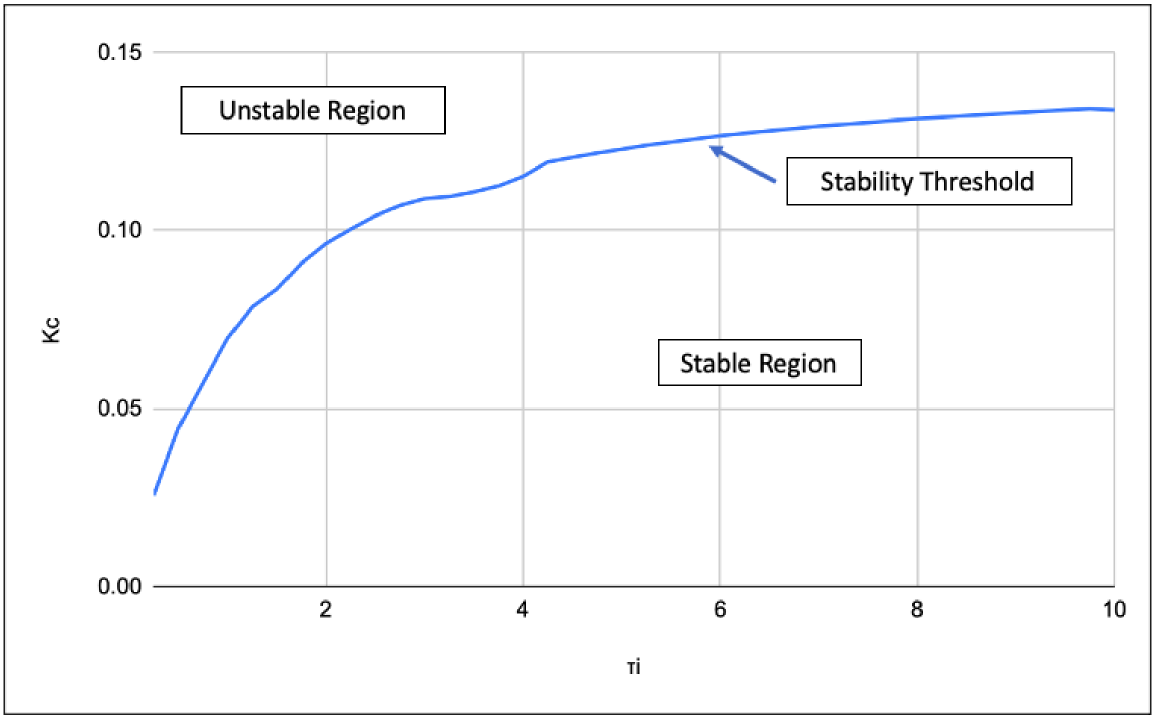

Figure 10 - Stability Threshold: System 1, Initial flow of 8.8 decreased to SP of 10. Combinations of Kc and τi below the stability threshold result in a stable process control.

The general relationship between Kc and τ_i depicted above for the stability threshold of a decrease in flow is consistent for an increase in flow and for process systems of varying size and amounts of controls, **Appendix D**. Increase in τ_i corresponds to an increasing Kc stability threshold that plateaus towards a maximum Kc. This is the maximum Kc for any given set of conditions the stability threshold approaches as τ_i approaches infinity. For any demand, there is a level of urgency (maximum Kc) that when passed, will cause a stable allocation of resource between competing demands to be impossible, independent of demand frequency. All area below stability threshold represents complete range of stable control parameters of a system. A larger area below stability threshold allows for more forgiveness in choosing control parameters in terms of maintaining process stability. As stated prior, it is important to remember that stability does not equate to successful process control. Rather stability should be treated as a first step or foundation of successful process control.

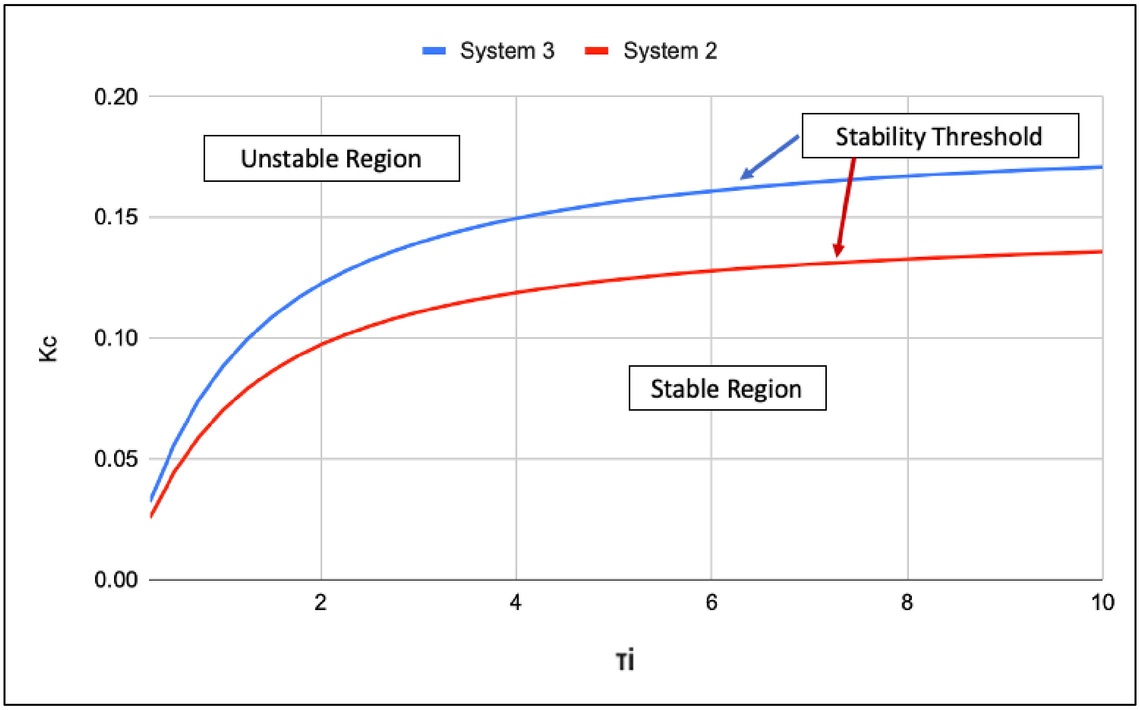

Figure 11 - Stability Threshold: Systems 2 and 3, Initial flow of 8.8 decreased to SP of 10. System 2 has one controlled outlet. System 3 has two controlled outlets. System 3 has a larger region for combinations of Kc and τi that result in stable control.

For a process with constant conditions, utilization of multiple controls (**System 3**) allows for a greater stability threshold range than that of a single control (**System 2**). There exists a tradeoff between lower max flow of fewer control **System 2**, and a larger array of stable control parameters of greater control **System 3**. For a process where control parameters are confident to fall within a stable control range it would be more beneficial to pursue fewer controllers to decrease max flow. Vice versa, if there is more confidence with the systems tolerance to high magnitude oscillations, it is more beneficial to pursue more controllers. This analysis should be treated as a single factor of many in deciding an optimal process system. Like choosing control parameters, the amount of control placed over a system of demands should be accessed at a case by case basis.

Speed of Stabilization

The process controls stabilization time is another important factor when choosing control parameters for a given system.

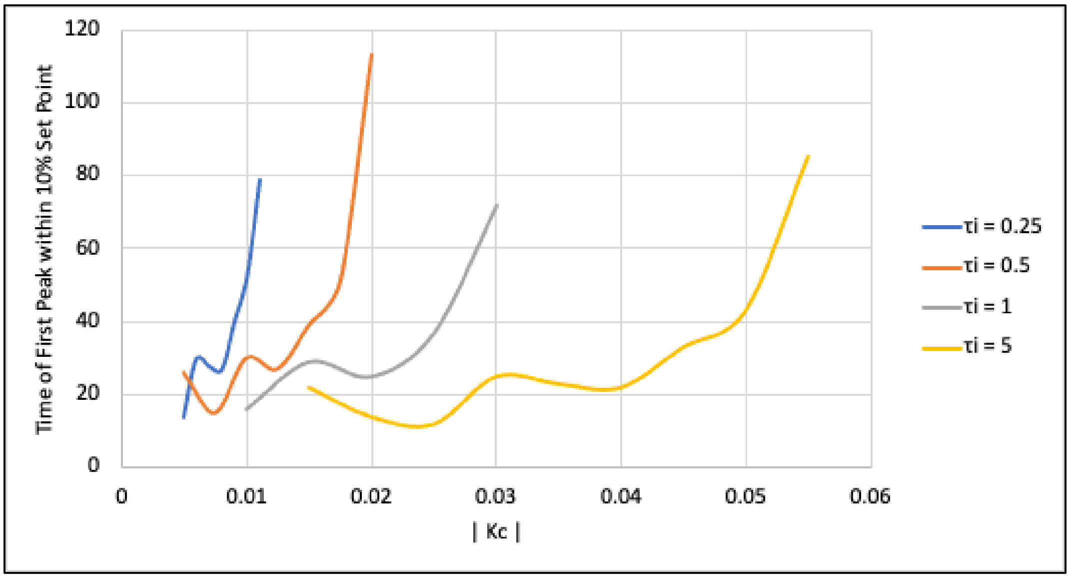

Figure 12 - Stability Time System 1. Initial flow of 8.8 increased to SP of 15. Increase in Kc and decrease in τi trend towards higher stabilization times.

Above shows the time at which the first oscillation peak stays confined within 10% of the desired set point. Here 10% is the stability tolerance. When the process variable is maintained within 10% of the SP the process is considered stabilized. This time is representative of the stabilization time of the system. Increase in Kc and/or decrease in τ_i causes an increase in stabilization time. Recording of stabilization time shows constant inconsistencies of stability times with overall trend, (seen in the bumpy curves of **Figure 12**,) suggesting that predictions should be given a marginal tolerance. Predictions close to a process's required stabilization time should be approached with skepticism. Trends of control parameter relationship with stabilization time and inconsistencies are constant with test carried out over all three systems.

Chapter 6 : Conclusion

In summary this thesis investigated the allocation of competing demands from the perspective of process control applied to a network flow system. The thesis utilized three systems with varying combinations of outlets flows and controls for this investigation.

The key findings of this thesis are that control demand characteristics of urgency and frequency, represented by control parameters Kc and inverse τ_i respectively, should be chosen based on system conditions following general trends investigated. Firstly, stability of any control must be maintained by choosing parameters that fall below a system's stability threshold. A stable process control is not necessarily successful. Kc and τ_i must be able to bring to the process variable to a desired set point without hurting its efficiency or security. Kc and τ_i must not cause the process to pass a systems maximum or minimum value of resource flow, be too slow to respond, or take too long to stabilize, in response to a change in desired set point. Calculating, evaluating, and balancing these control parameter impacts will be dependent on the process and system conditions.

Utilization of multiple controls on a given system will follow the same general parameter trends. This thesis found that a system of more controls will allow for a greater range of stability parameters but increase the maximum flow value for those given parameters. Addressing an ideal number of controls must be assessed on a case by case system.

For a well-known system this thesis suggests that the system wide outcomes of a change in desired set point can be predicted. This would allow an indirect control over other aspects of a process and incredible utilization of a minimal number of controls. This idea can be further investigated in future work.

Other future endeavors along the lines of this thesis include implementing a turbulent switch to the current laminar flow models and addressing its new implications. Multilayer flow systems, multiple input systems, and introduction of capacity within the system are also possible expansions upon this work. A lot more can be investigated on the control side of this study. The addition of deadtime variance, multiple controls of differing parameters, PID control, or system disturbances could be interested next steps for similar work.

Appendix A : Process Control Diagram

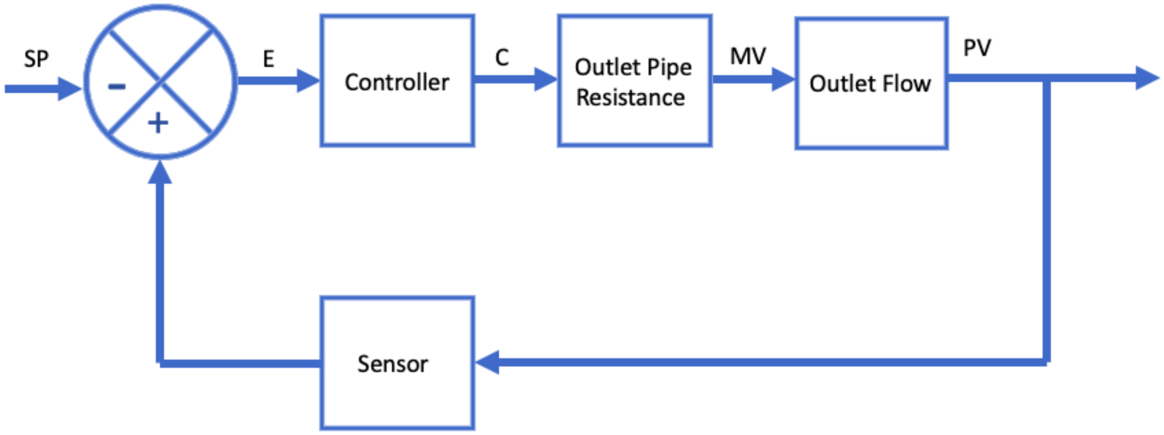

Figure 13 - Process Control on Fluid Flow System

Appendix B : Systems

System 1:

Pipe	L	r	Ro
P1	1.00	0.10	25.46
P3	2.00	0.10	50.93
P4	2.00	0.10	50.93

Table 1 - System 1: Pipe Parameters and resulting initial Resistance

Pressure	
1	1000
3	100
4	100

Table 2 - System 1: Pressure

Controller	
Kc	*INSERT*
τ_i	*INSERT*
θp	1
Time step	0.5
τ_i, steps	τ_i / 0.5
θp, steps	2
SP for stream 3	*INSERT*

Table 3 – System 1: Controller Parameters

Initial Results	
ΔP1	450
ΔP3	450
ΔP4	450
Q1	17.6715
Q3	8.8357
Q4	8.8357

Table 4 – System 1: Initial Results

System 2 and 3:

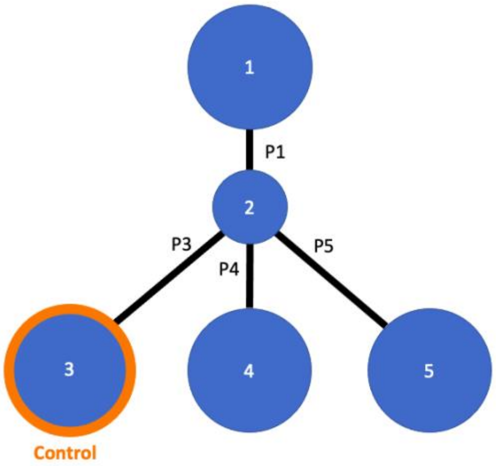

Figure 14 - System 2

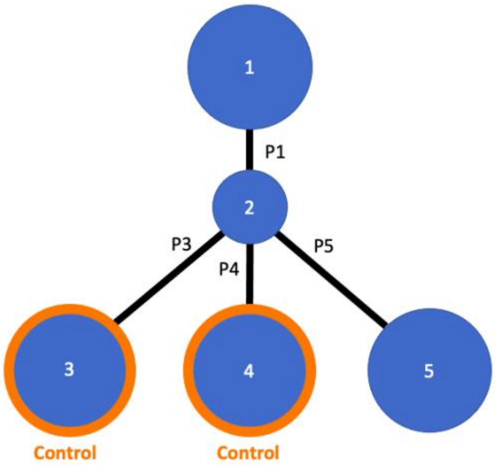

Figure 15 - System 3

System 2 and 3 have the same system conditions and initial parameters:

Pipe	L	r	Ro
P1	1.00	0.10	25.46
P3	2.00	0.10	50.93
P4	2.00	0.10	50.93
P5	2.00	0.10	50.93

Table 5 – System 2 and 3: Pipe Parameters and resulting initial Resistance

Pressure (Pa)	
1	850
3	100
4	100
5	100

Table 6 – System 2 and 3: Pressure

Controller	
Kc	*INSERT*
τ_i	*INSERT*
θp	1
Time step	0.5
τ_i, steps	τ_i / 0.5
θp, steps	2
SP for stream 3	*INSERT*

Table 7 – System 2 and 3: Controller Parameters

Initial Results	
ΔP1	450
ΔP3	300
ΔP4	300
ΔP5	300
Q1	17.6715
Q3	8.8357
Q4	8.8357
Q5	8.8357

Table 8 – System 2 and 3: Initial Results

Appendix C : Testing Specifics

Throughout thesis, all tests are carried out with constant values of L, r, P, θp, and ts for each given system. These values are explicitly defined in **Appendix B**. All tests view the first 100 time values, first 200 time steps, of data.

Max Flow

The test intention is to generate a graphical representation of how the maximum inlet flow (Q1) is impacted by change in control parameters Kc and τ_i.

Starting with **System 1** implement an increase in desired flow by setting SP to 10. Input a τ_i value of 0.25 into controller. Input a low Kc value of -0.001 into the controller and record the resulting maximum inlet flow value (Q1) over the first 200 time steps. Keeping constant τ_i increase the magnitude of Kc in set increments until process loses stability, **Figure 3**. For each Kc record the resulting maximum inlet flow. Repeat this process for increasing τ_i values (ei. 0.5, 1, 2, 5). Kc initial values and increase increments are adjusted depending on τ_i value. (Greater τ_i value allows for greater initial Kc values and increase increments.) Record all maximum inlet flow values and graph vs Kc, each τ_i will be a separate line. Repeat this process for **System 2** and **System 3**.

Stability Threshold

Here test intention is to generate graphical depiction of a stability threshold for the three system. Starting with **System 1**, implement a decrease in desired flow by setting SP to 5. Initially, set τ_i to zero and adjust Kc gain so that the fluid flow system resembles ringing oscillations for controlled flow (Q3) vs time, **Figure 3**. This scenario is mathematically confirmed by comparing the maximum value of the first and second 100 steps of flow data. Each maximum represents the highest peak of each half of process variable values. Here adjust Kc so that the difference in maximum peak values in minimized around a graphically apparent ringing oscillation. The value of Kc with this minimum peak difference is the stability threshold for the given τ_i. Increase τ_i by increments of 0.25 up to 10, repeating this process for each increase. Graph recorded Kc values with their corresponding τ_i values.

Repeat this process for **System 2** and **System 3**. Carry out this process again for **System 1**, instead implementing an increase in desired flow by setting SP to 10.

Stabilization Time

The test intention is to generate graphical representation of the relationship between control parameters Kc and τ_i and stabilization time. For this test control stabilization time is represented as the time required for the process variable (Q3) to reach a point where oscillation peaks stay within a specific range around the desired SP. Here the specific range, or stability threshold, is set to 10%. In other words, for a SP of 10, the time of the first oscillation peak below a value of 11 (110% of SP) is representative of the stabilization time.

This test applied conditional formatting to the column of Q3 data over time. Cells below the SP were formatted to appear blue, symbolizing this was data during a trough. Cells above the stability thresholds increase on the SP (11) were formatted to appear red, symbolizing the process was not yet considered stabilized. For any given peak, non-blue consecutive cells, if no cells were red there was a stabilized peak. The time correlating to the maximum value (Q3) of the first of these stabilized peaks was considered the stabilization time.

Starting with **System 1** implement an increase in desired flow by setting SP to 15. Input a τ_i value of 0.25 into controller. Input a low Kc value of -0.001 into the controller and record the stabilization time. Using the method stated above record the stabilization time for the Kc value for τ_i. If there are no peaks within the sample data set, the flow has not reached the SP, exclude that Kc value from the recorded data. Increase Kc by set increments until there are no stabilized peaks in the data set. Repeat this process for increasing τ_i values. Kc initial values and increase increments are adjusted depending on τ_i value. Record stabilization time values and graph vs Kc, each τ_i will be a separate line.

Repeat this process for **System 2** and **System 3** at a SP of 10.

Appendix D : Additional Graphs

Max Flow Testing:

Relationship trends between Kc and τi and max flow are constant for **Systems 1, 2, and 3**.

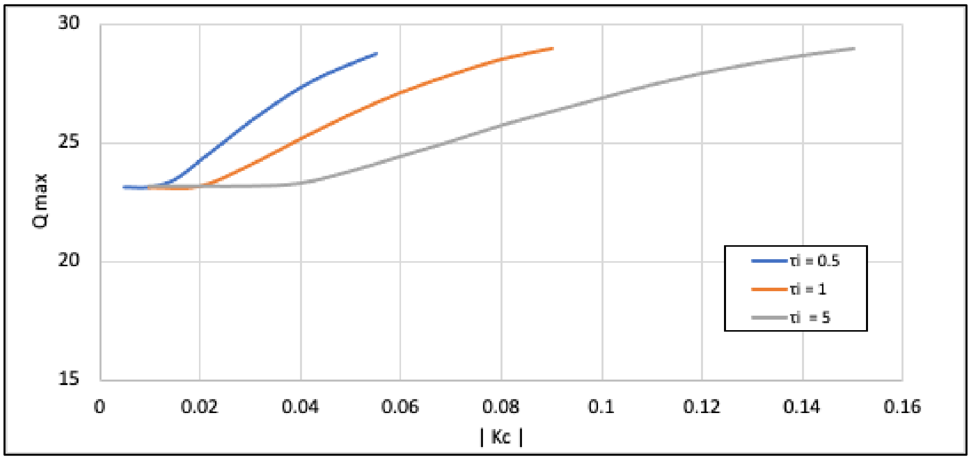

Figure 16 - System 2: Max Flow Data. Increase in Kc and decrease in τi increase Q max (PV).

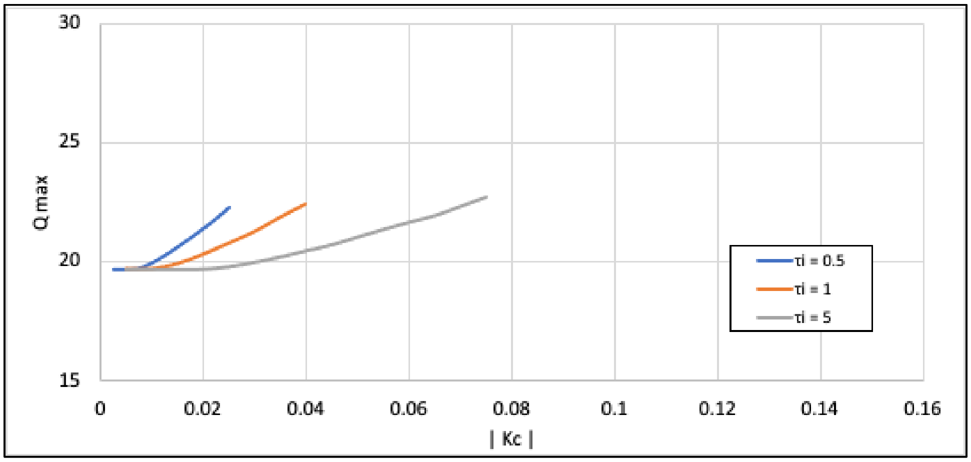

Figure 17 - System 3: Max Flow Data. Increase in Kc and decrease in τi increase Q max (PV).

Stability Threshold Testing:

Relationship trends between Kc and τi and stability threshold are constant for both SP above and below initial flow.

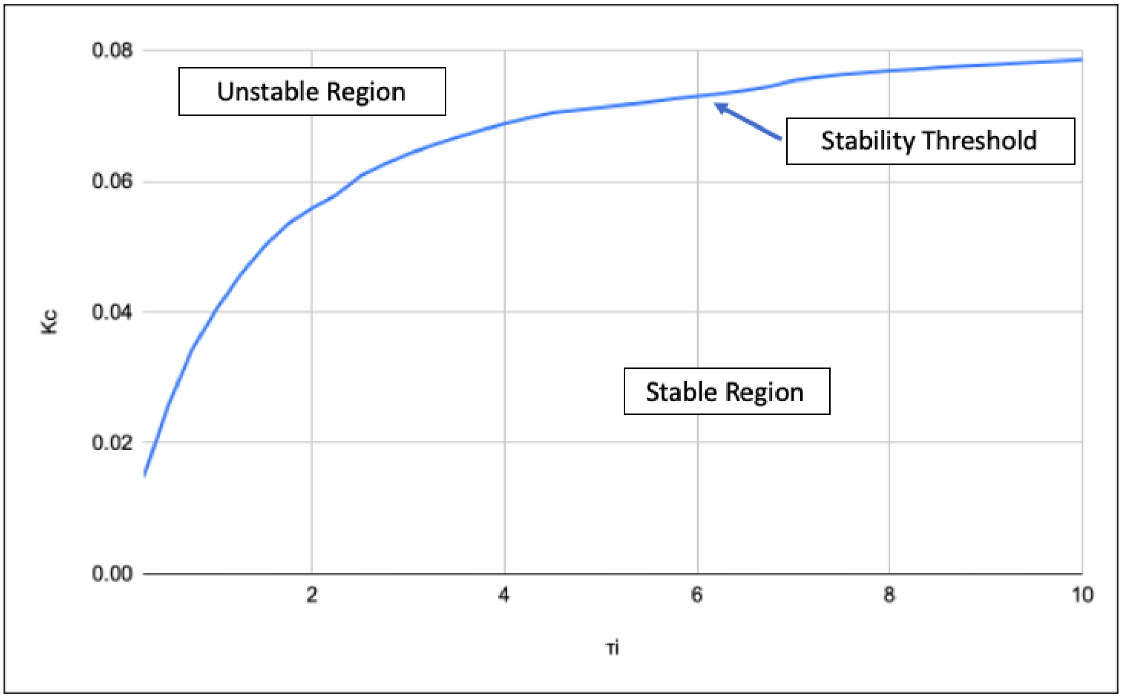

Figure 18 - Stability Threshold: System 1, Initial flow of 8.8 increased to SP of 10. Combinations of Kc and τi below the stability threshold result in a stable process control.

Stabilization Time Testing:

Relationship trends between Kc and τi and stabilization time are constant for **Systems 1, 2, and 3.**

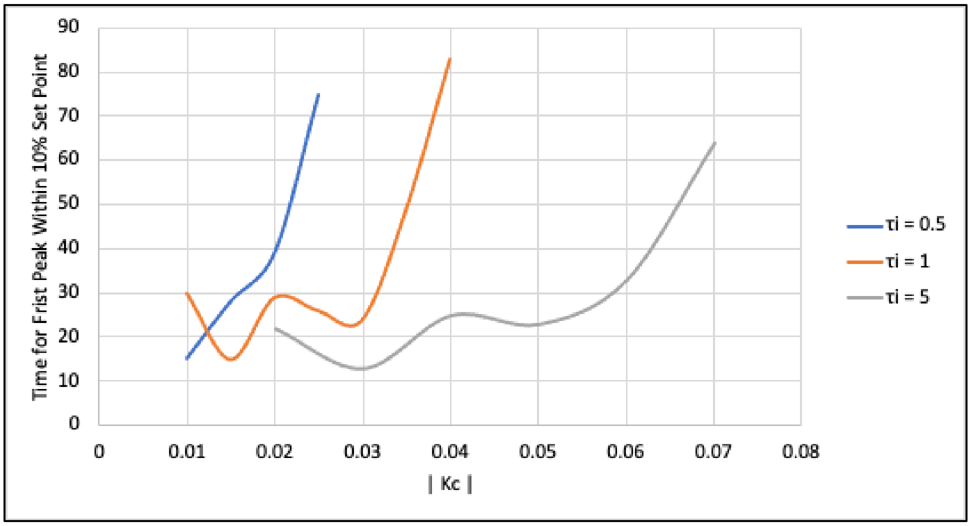

Figure 19 - Stability Time System 2: Initial flow of 8.8 increased to SP of 10. Increase in Kc and decrease in τi trend towards higher stabilization times.

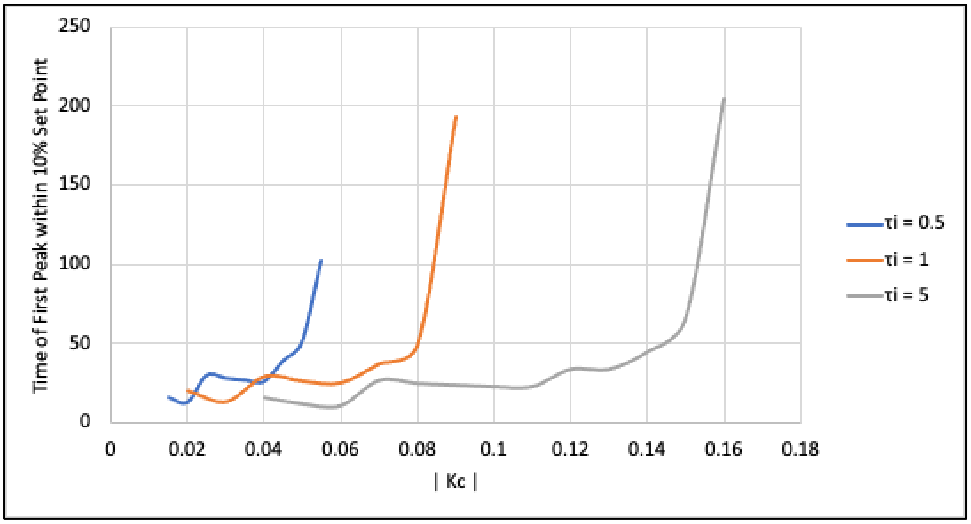

Figure 20 - Stability Time System 3: Initial flow of 8.8 increased to SP of 10. Increase in Kc and decrease in τi trend towards higher stabilization times.

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Bachelor of Science in Chemical Engineering, Graduation May 2022
Minor in Environmental Engineering
The Pennsylvania State University, University Park, PA
Schreyer Honors College Student,

Experience

Sentry Engineering Intern, KCF Technologies, State College, PA Summer 2021

- Communicated with customers and engineering team to assure machine health through continuous vibrational monitoring
- Conducted motion amplification and phase analysis in the form of a technical report for a critical asset of a chemical customer
- Updated the SMARTdiagnostics monitoring service site of a chemical customer

Researcher, Chemical Engineering Department Spring 2021 – Present
The Pennsylvania State University, University Park, PA

- Created Excel models to analyze balancing competing demands through process control of a fluid flow system
- Examined stability limits and optimal outcome of applied process control

Donor Relations Chair, Help Every Angel Live (HEAL), THON Organization, March 2020 – Present
University Park, PA

- Facilitated organization’s traditional fundraisers
- Co-led weekly meetings and presented updates on fundraising goals
- Represented the organization and aided in creating an open and friendly atmosphere for new and returning members

Package Handler, FedEx, Middletown, CT Summer 2020

- Applied Covid-19 safety measures while working with a diverse team

Sustainability Chair, Dancer Relations THON Committee, School Year 2019-2020
THON, University Park, PA

- Monitored and was responsible for the physical and mental well-being of dancers during THON weekend’s 46 hour dance marathon
- Maintained ecofriendly practices and co-facilitated recycling fundraisers

Learning Assistant, Chemistry Department Fall Semester 2019
The Pennsylvania State University, University Park, PA

- Responded to students’ questions during lecture and worked with a graduate student to run weekly recitation sessions
- Led pre-exam review sessions to resolve student confusion and stress by solving practice questions and explaining concepts

Lab Assistant, Inorganic Nanomaterials Research Lab Summer 2017
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- Experimented with the synthesis of gold cube nanoparticles to modify a procedure for improved accuracy and efficiency

Sandwich Artist, Subway, Deep River, CT Summer 2019

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