CS342301: Operating System

Pthreads Programming Assignment:

Producer-Consumer Problem

Team31

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	Contribution
劉祐廷	1. Do experiments and process results 2. Discuss and complete the entire report.
黃子恩	1. Implement code 2. Do experiments and process results 3. Discuss and complete the entire report.

OS Pthread

Implementation

main

```
int main(int argc, char** argv) {
    assert(argc == 4);

    int n = atoi(argv[1]);
    std::string input_file_name(argv[2]);
    std::string output_file_name(argv[3]);

    TSQueue<Item*> reader_queue(READER_QUEUE_SIZE);
    TSQueue<Item*> worker_queue(WORKER_QUEUE_SIZE);
    TSQueue<Item*> writer_queue(WRITER_QUEUE_SIZE);
    Transformer transformer;
    // TODO: implements main function
    Reader* reader = new Reader(n, input_file_name, &reader_queue);
    Producer* producer1 = new Producer(&reader_queue, &worker_queue,
&transformer);
    Producer* producer2 = new Producer(&reader_queue, &worker_queue,
&transformer);
    Producer* producer3 = new Producer(&reader_queue, &worker_queue,
&transformer);
    Producer* producer4 = new Producer(&reader_queue, &worker_queue,
&transformer);
    Writer* writer = new Writer(n, output_file_name, &writer_queue);
    ConsumerController* consumer_controller = new ConsumerController(
        &worker_queue,
        &writer_queue,
        &transformer,
        CONSUMER_CONTROLLER_LOW_THRESHOLD_PERCENTAGE,
        CONSUMER_CONTROLLER_HIGH_THRESHOLD_PERCENTAGE,
        CONSUMER_CONTROLLER_CHECK_PERIOD
    );

    reader->start();

    producer1->start();
    producer2->start();
    producer3->start();
    producer4->start();

    consumer_controller->start();

    writer->start();

    reader->join();
```

```
    writer->join();

    // Clean up resources
    delete reader;
    delete producer1;
    delete producer2;
    delete producer3;
    delete producer4;
    delete consumer_controller;
    delete writer;

    return 0;
}
```

首先根據設置好的 queue_size 宣告 reader_queue, worker_queue 以及 output_queue。接著創建 Reader, Producers, Consumer_controller 以及 Writer，依序開始執行。最後等待 Reader 及 Writer 執行結束並釋放資源。

Ts_Queue

TSQueue<T>::TSQueue

TSQueue的建構子，設置各個變數的初始值，並初始化互斥鎖及 conditional variables。

```
template <class T>
TSQueue<T>::TSQueue(int buffer_size) : buffer_size(buffer_size) {
    // TODO: implements TSQueue constructor
    this->buffer = new T[this->buffer_size];
    //this->buffer_size = 0;
    this->head = 0;
    this->size = 0;
    this->tail = 0;
    pthread_mutex_init(&this->mutex, nullptr);
    pthread_cond_init(&this->cond_enqueue, nullptr);
    pthread_cond_init(&this->cond_dequeue, nullptr);
}
```

TSQueue<T>::~TSQueue

TSQueue的解構子，釋放各個變數的資源並銷毀互斥鎖及 conditional variable。

```
template <class T>
TSQueue<T>::~TSQueue() {
    // TODO: implenents TSQueue destructor
    delete[] buffer;
    pthread_mutex_destroy(&this->mutex);
    pthread_cond_destroy(&this->cond_enqueue);
```

```
    pthread_cond_destroy(&this->cond_dequeue);
}
```

TSQueue<T>::enqueue

首先,取得 lock 以避免其他 threads 同時對 queue 進行操作。若 queue 為滿的狀態，則呼叫 pthread_cond_wait(&this->cond_enqueue, &this->mutex)，等待其他 threads 進行 dequeue 後的 signal。若 queue 仍有空間，則將 item 放入最後端(head處)，並更新 size 及 head 的值(這邊採用的是 circular queue)。enqueue 的操作結束後呼叫 pthread_cond_signal，喚醒正在 waiting cond_dequeue 的 thread (現在的 queue 裡有 item 可以做 dequeue 了)。接著使用 pthread_mutex_unlock 釋放互斥鎖，讓其他 threads 得以存取 queue。

```
template <class T>
void TSQueue<T>::enqueue(T item) {
    // TODO: enqueues an element to the end of the queue
    pthread_mutex_lock(&this->mutex);
    while(this->head == this->tail && this->size == this->buffer_size) {
        pthread_cond_wait(&this->cond_enqueue, &this->mutex);
    }
    this->buffer[this->head] = item;
    this->head = (this->head + 1) % this->buffer_size;
    this->size++;
    pthread_cond_signal(&this->cond_dequeue);
    pthread_mutex_unlock(&this->mutex);
}
```

TSQueue<T>::dequeue

首先，使用 pthread_mutex_lock 取得 lock 以避免其他 threads 同時對 queue 進行操作。若 queue 為空，則呼叫 pthread_cond_wait(&this->cond_dequeue, &this->mutex)，等待其他 threads 進行 enqueue 後的 signal。若仍有 items 在 queue 之中，則將最前端的 item 取出(tail處)，更新 size 及 tail 的值(這邊採用的是 circular queue)，最後將取出的 item 回傳。dequeue 的操作結束後呼叫 pthread_cond_signal，喚醒正在 waiting cond_enqueue 的 thread (現在的 queue 有空間可以做 enqueue 了)。接著使用 pthread_mutex_unlock 釋放互斥鎖，讓其他 threads 得以存取 queue。

```
template <class T>
TSQueue<T>::dequeue() {
    // TODO: dequeues the first element of the queue
    pthread_mutex_lock(&this->mutex);
    while(this->tail == this->head  && this->size == 0){
        pthread_cond_wait(&this->cond_dequeue, &this->mutex);
    }
    T item = this->buffer[this->tail];
    this->tail = (this->tail + 1) % this->buffer_size;
    this->size--;
    pthread_cond_signal(&this->cond_enqueue);
    pthread_mutex_unlock(&this->mutex);
```

```
        return item;
    }
```

TSQueue<T>::get_size

回傳 private 變數 size，用以取得目前 queue 中 item 的數量。使用 pthread_mutex_lock 取得互斥鎖，以避免其他 threads 同時對 size 進行操作。結束後使用 pthread_mutex_unlock 釋放互斥鎖，讓其他 threads 得以存取 size。

```
template <class T>
int TSQueue<T>::get_size() {
    // TODO: returns the size of the queue
    pthread_mutex_lock(&mutex);
    int current_size = this->size;
    pthread_mutex_unlock(&mutex);
    return current_size;
}
```

Reader

Reader::start

創建執行 Reader::process 的 Reader thread，其中: 參數 1: &t 是執行緒變數，儲存新建立的執行緒 ID。參數 2: 0 表示使用預設的執行緒屬性。 參數 3: Reader::process 是執行緒的起始函數。 參數 4: (void*)this 將當前物件的指標傳遞給執行緒函數。

```
void Reader::start() {
    pthread_create(&t, 0, Reader::process,(void*)this);
}
```

Reader::process

根據 expected_lines，依次從檔案流(ifs)中讀取指定行數的資料。為每一行資料動態分配一個 Item 物件，並將初始化完成的 Item 放入 input_queue，供後續處理使用(enqueue)。

```
void* Reader::process(void* arg) {
    Reader* reader = (Reader*)arg;
    while (reader->expected_lines--) {
        Item *item = new Item;
        reader->ifs >> *item;
        reader->input_queue->enqueue(item);
    }
    return nullptr;
}
```

Producer

Producer::start

創建執行 Producer::process 的 Producer thread

```
void Producer::start() {
    // TODO: starts a Producer thread
    pthread_create(&t, 0, Producer::process, (void*)this);
}
```

Producer::process

從 input_queue 中 dequeue，取出最前端的item。接著將 item->opcode 及 item->val 傳入 producer_transform 並將 item->val 更新為回傳值。最後，將 item 放入 worker_queue 中(enqueue)。

```
void* Producer::process(void* arg) {
    // TODO: implements the Producer's work
    Producer* producer = (Producer*)arg;

    while(true) {
    Item * item = producer->input_queue->dequeue();
    item->val = producer->transformer->producer_transform(item->opcode, item-
>val);
    producer->worker_queue->enqueue(item);
    }
    return nullptr;
}
```

Consumer_controller

ConsumerController::start

創建執行 ConsumerController::process 的 ConsumerController thread

```
void ConsumerController::start() {
    // TODO: starts a ConsumerController thread
    pthread_create(&t, 0, ConsumerController::process, (void*)this);
}
```

ConsumerController::process

每 CONSUMER_CONTROLLER_CHECK_PERIOD 微秒檢查一次 worker_queue 的狀態。如果 worker_queue 中 item 的數量超過 high_threshold(%)，則創建一個新的 Consumer thread 來處理工作。反之，如果 worker_queue 中 item 的數量低於 low_threshold(%)，則將最新創建的 Consumer thread 砍掉（透過呼叫

Consumer->cancel 方法），此時須確保至少仍有一個 Consumer 在運作。其中，我們使用 ConsumerController::consumers 來紀錄目前正在執行的 Consumer 清單。

```
void* ConsumerController::process(void* arg) {
    // Cast the argument to ConsumerController
    ConsumerController* controller = static_cast<ConsumerController*>(arg);
    while (true) {
        // Get the current size of the worker queue
        int worker_queue_size = controller->worker_queue->get_size();
        if (worker_queue_size > controller->worker_queue->buffer_size *
controller->high_threshold / 100){
            // Add a new consumer
            Consumer* new_consumer = new Consumer(
                controller->worker_queue,
                controller->writer_queue,
                controller->transformer
            );

            new_consumer->start(); // Start the consumer thread
            controller->consumers.push_back(new_consumer);

            std::cout << "Scaling up consumers from "<< controller-
>consumers.size() - 1 <<  " to " << controller->consumers.size() << std::endl;
        }
        // Scale down consumers if the worker queue falls below the low threshold
        else if (worker_queue_size < controller->worker_queue->buffer_size *
controller->low_threshold / 100 && controller->consumers.size() > 1) {
            // Remove the most recently added consumer
            Consumer* last_consumer = controller->consumers.back();
            last_consumer->cancel(); // Cancel the consumer thread
            last_consumer->join();   // Wait for the thread to finish
            //delete last_consumer;    // Free memory

            controller->consumers.pop_back();
            std::cout << "Scaling down consumers from "<< controller-
>consumers.size() + 1 <<  " to " << controller->consumers.size() << std::endl;

        }

        // Ensure there is always at least one consumer


        // Sleep for the check period
        usleep(controller->check_period);
    }
    return nullptr;
}
```

Consumer

Consumer::start

創建執行 Consumer::process 的 Consumer thread

```
void Consumer::start() {
    // TODO: starts a Consumer thread
    pthread_create(&t, 0, Consumer::process, (void*)this);
}
```

Consumer::cancel

將 Consumer 中的 is_cancel 設為 true，代表該 Consumer 即將被砍掉。

```
int Consumer::cancel() {
    is_cancel = true;
    return 0;
}
```

Consumer::process

將此 Consumer thread 的取消型態設定為「延遲型」（PTHREAD_CANCEL_DEFERRED），表示 thread 僅在安全點（如 pthread_testcancel）檢查取消請求。

若 consumer->is_cancel 為 true ，則不再執行，並將此 consumer thread 刪除。

若 consumer->is_cancel 為 false，則將 此 Consumer thread 設為不能取消的狀態，確保工作不會在處裡過程中因此 Consumer thread 被取消而被中斷。從 worker_queue 中 dequeue，取出最前端的item。接著將 item->opcode 及 item->val 傳入 consumer_transform 並將 item->val 更新為回傳值。最後，將 item 放入 output_queue 中(enqueue)。

在完成工作邏輯後將此 Consumer thread 恢復到可以取消的狀態，使其能夠接收取消請求。

```
void* Consumer::process(void* arg) {
    Consumer* consumer = (Consumer*)arg;
    pthread_setcanceltype(PTHREAD_CANCEL_DEFERRED, nullptr);
    while (!consumer->is_cancel) {
        // TODO: implements the Consumer's work
        pthread_setcancelstate(PTHREAD_CANCEL_DISABLE, nullptr);
        Item *item = consumer->worker_queue->dequeue();
        item->val = consumer->transformer->consumer_transform(item->opcode, item-
>val);
        consumer->output_queue->enqueue(item);
        pthread_setcancelstate(PTHREAD_CANCEL_ENABLE, nullptr);
    }
    delete consumer;
    return nullptr;
}
```

Writer

Writer::start

創建執行 Writer::process 的 Writer thread

```
void Writer::start() {
    // TODO: starts a Writer thread
    pthread_create(&t, 0, Writer::process, (void*)this);
}
```

Writer::process

從 output_queue 中 dequeue，取出最前端的item。接著將該 item 傳入輸出流(ofs)中輸出，並將該 item 刪除，釋放資源。

```
void* Writer::process(void* arg) {
    // TODO: implements the Writer's work
    Writer* writer = (Writer*)arg;
    while(writer->expected_lines--){
        Item* item = writer->output_queue->dequeue();
        writer->ofs << *item;
        delete item;
    }
    return nullptr;
}
```

Experiment

Different values of CONSUMER_CONTROLLER_CHECK_PERIOD

Discussion

減少 check period time 可以更及時的分配資源，因此可以增快執行速度，但是太過頻繁的檢查並調度也會花費更多的時間，因此可以在 test 01 1/10 times check period 的測試中看到，其執行速度沒有比 1/2 times check period 的速度更快，因此 check period time 應該是有一個最佳表現區間，太大或太小都會導致執行速度低落。

Result

- **test 00 Runtime**

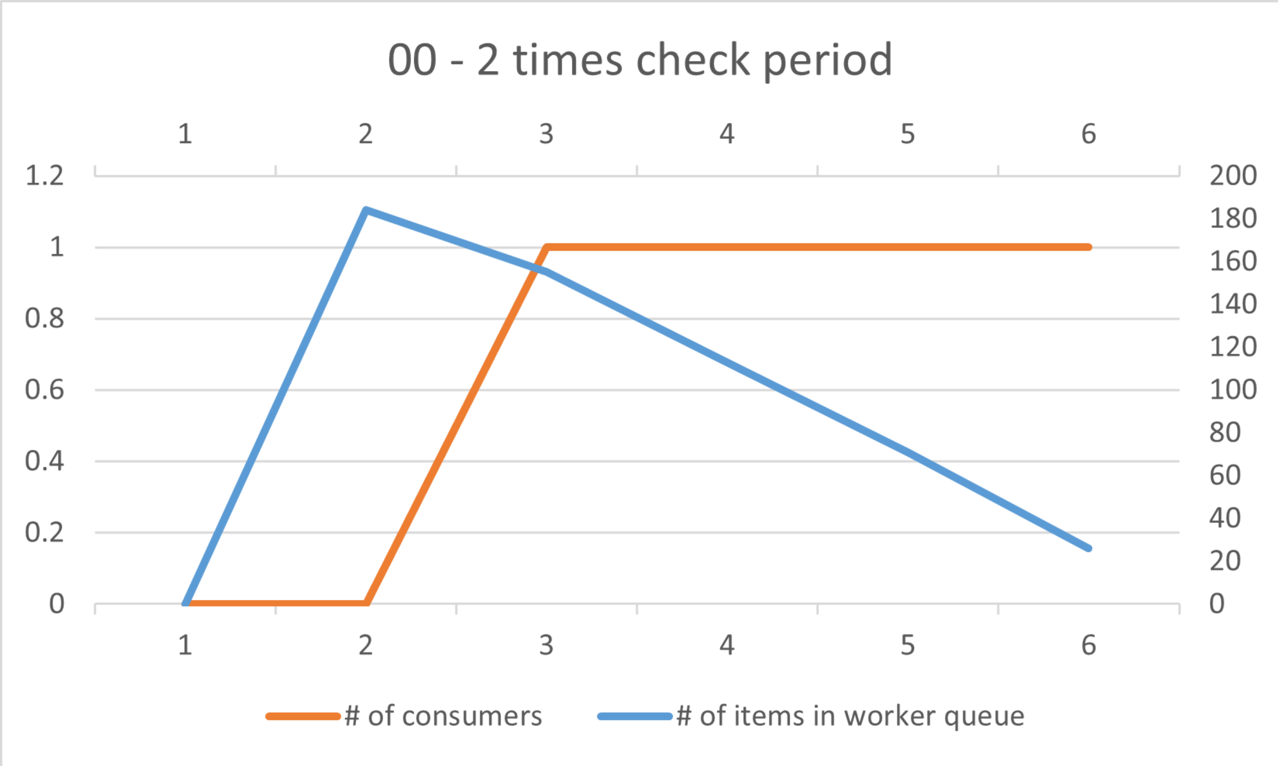
Check period	Runtime
2 times	11.1133
1 times	7.25883

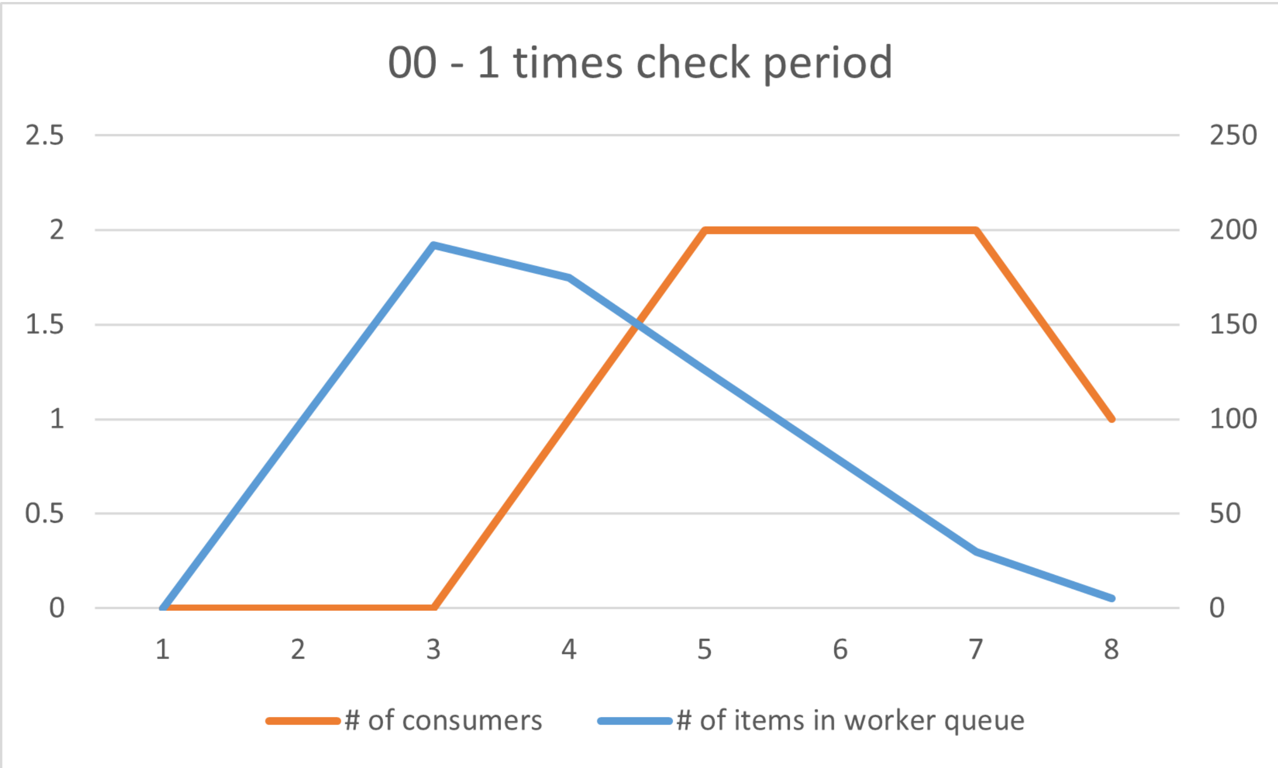
Check period	Runtime
1/2 times	5.39247
1/10 times	3.46049

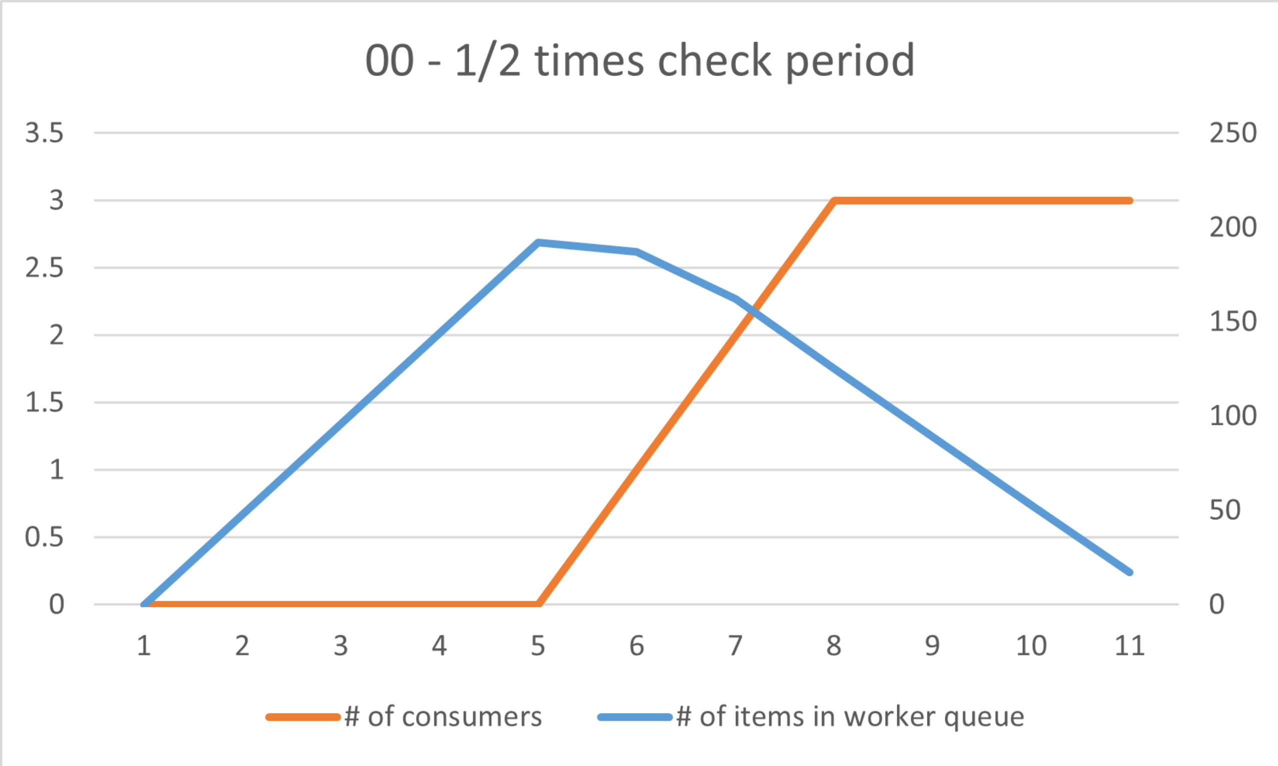
- **test 01 Runtime**

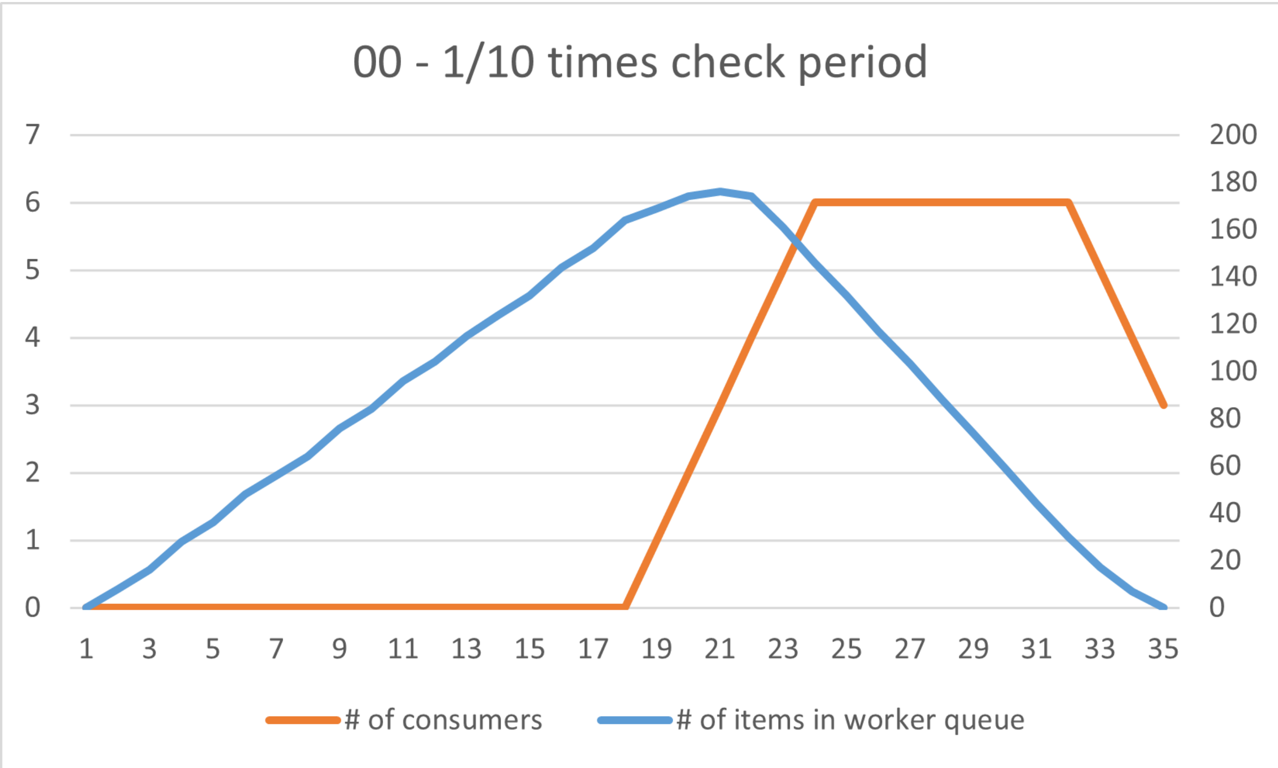
Check period	Runtime
2 times	68.8665
1 times	59.7507
1/2 times	52.8105
1/10 times	52.8789

- **test 00 Figures**

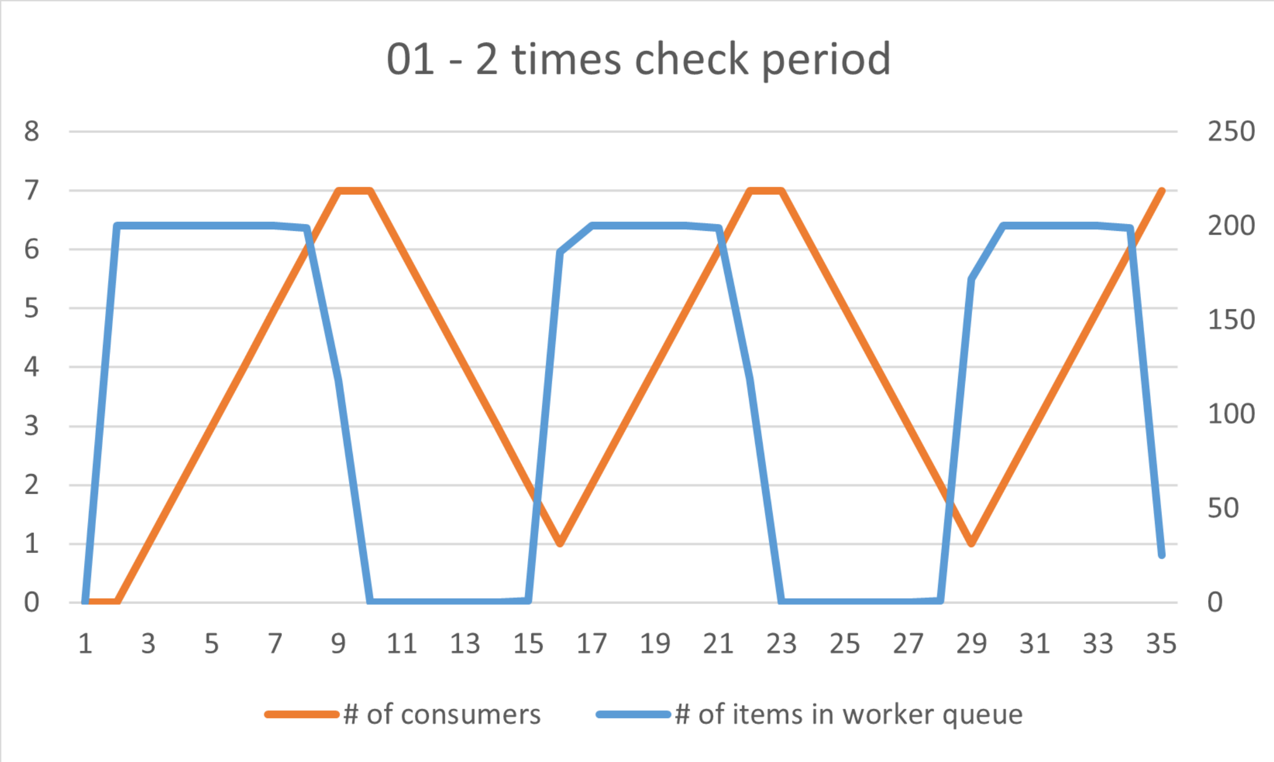

00 - 2 times check period
1
2
3
4
5
6
1.2
1
0.8
0.6
0.4
0.2
0
200
180
160
140
120
100
80
60
40
20
0
# of consumers
# of items in worker queue

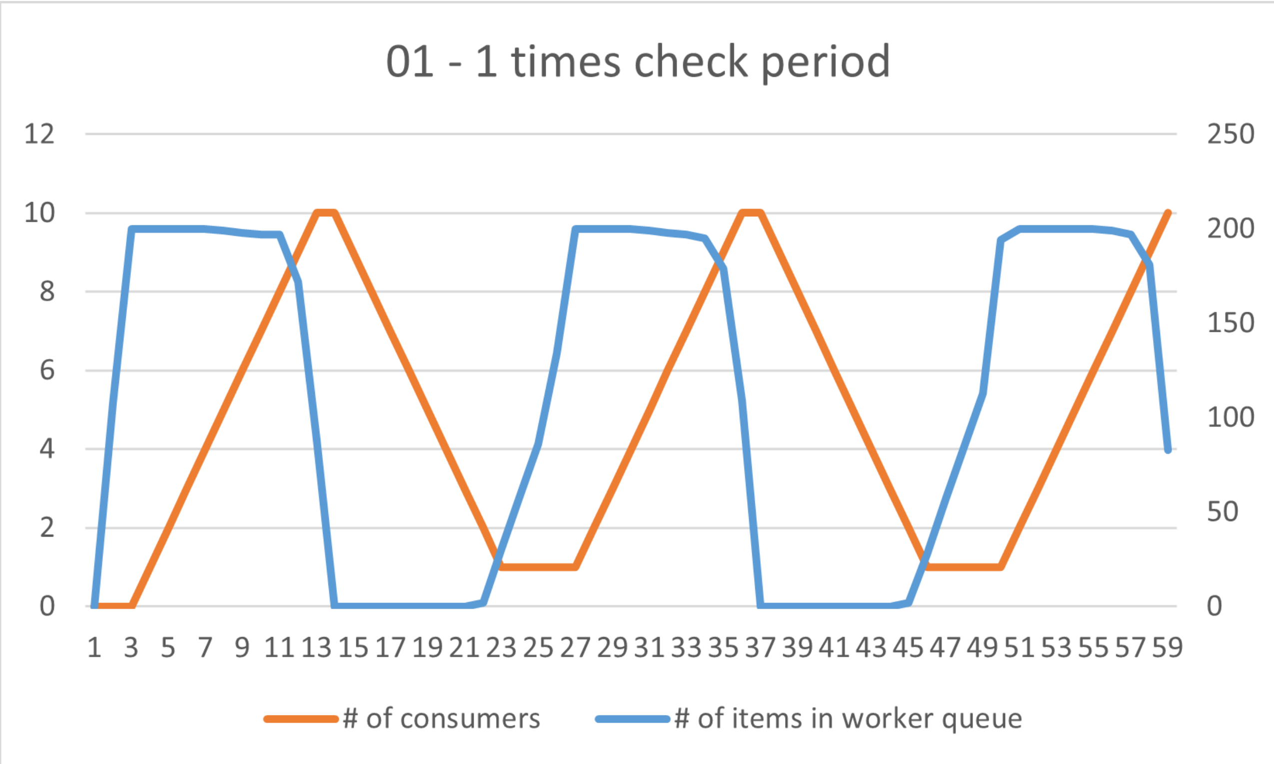

00 - 1 times check period
2.5
2
1.5
1
0.5
0
250
200
150
100
50
0
1
2
3
4
5
6
7
8
# of consumers
# of items in worker queue

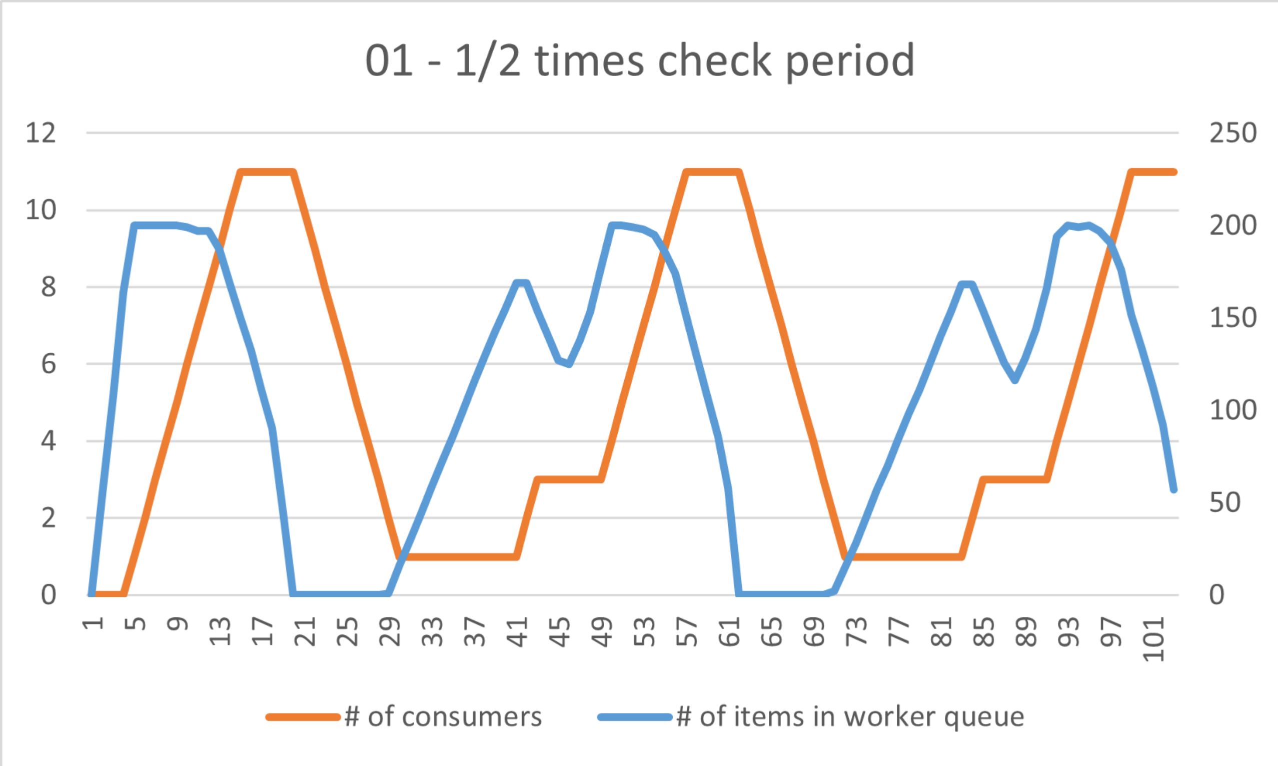


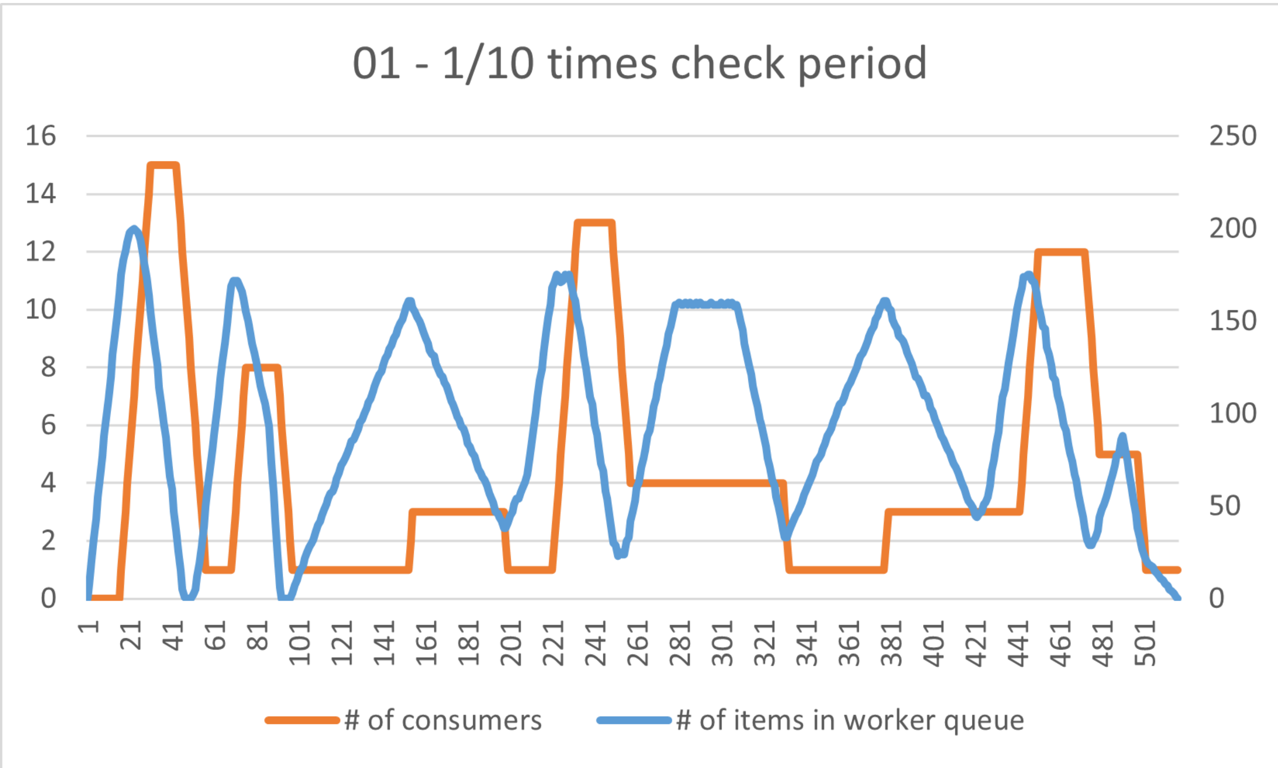


- **test 01 Figures**


01 - 2 times check period
8
7
6
5
4
3
2
1
0
250
200
150
100
50
0
1 3 5 7 9 11 13 15 17 19 21 23 25 27 29 31 33 35
# of consumers
# of items in worker queue


01 - 1 times check period
12
10
8
6
4
2
0
250
200
150
100
50
0
1 3 5 7 9 11 13 15 17 19 21 23 25 27 29 31 33 35 37 39 41 43 45 47 49 51 53 55 57 59
# of consumers
# of items in worker queue





Different values of CONSUMER_CONTROLLER_LOW_THRESHOLD_PERCENTAGE and CONSUMER_CONTROLLER_HIGH_THRESHOLD_PERCENTAGE

Discussion

從 test 00 看起來，較小的 min threshold 與較小的 max threshold 執行速度更快，但當數量放大之後，從 test 01 的結果可以看出，這兩個 threshold 的設置對於執行速度上的影響甚微。

Result

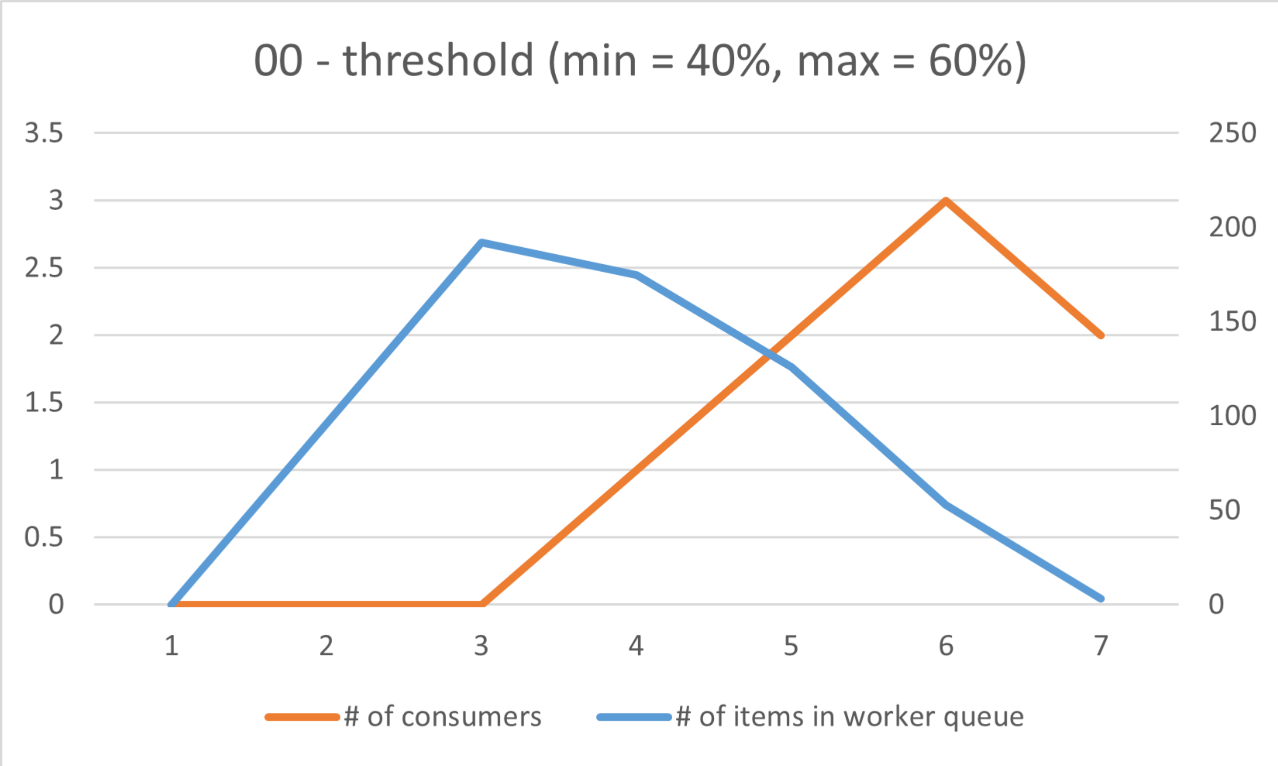
- **test 00 Runtime**

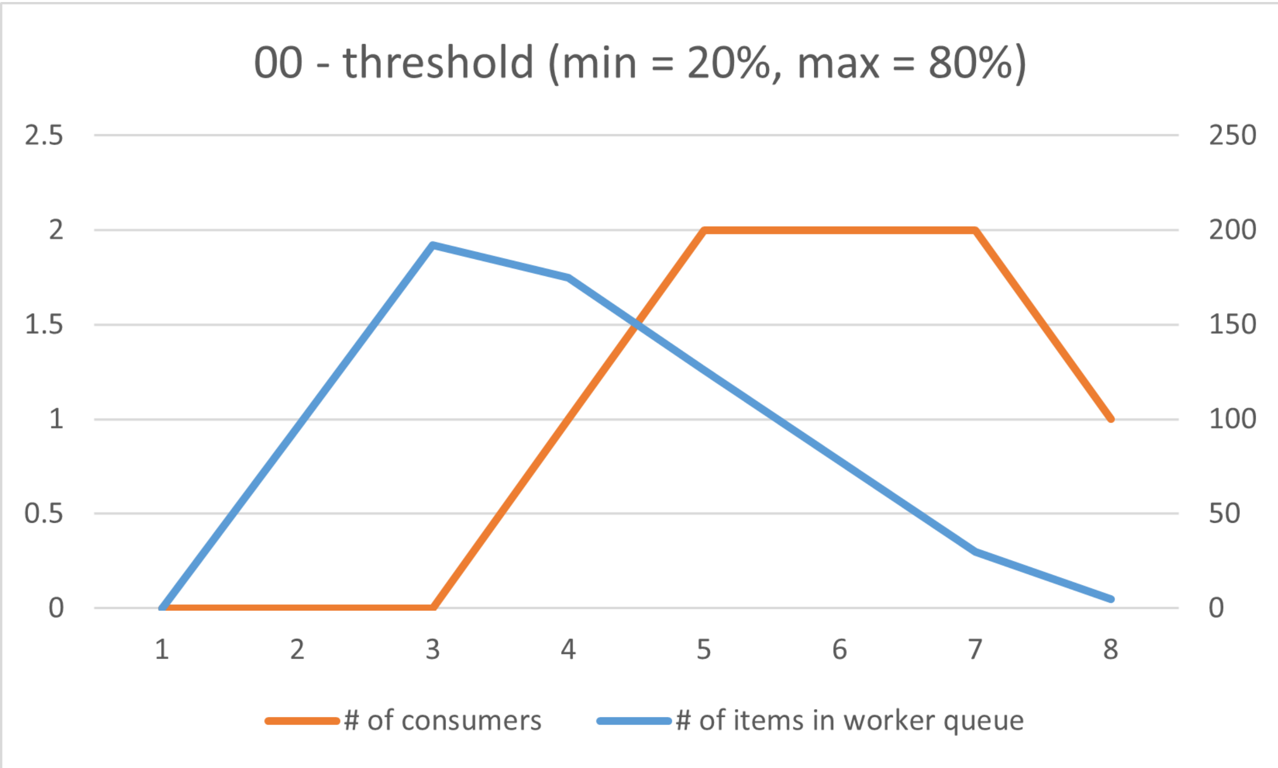
Threshold (min, max)	Runtime
(40%, 60%)	6.17829
(20%, 80%)	7.25883
(20%, 60%)	5.77848
(40%, 80%)	8.25213

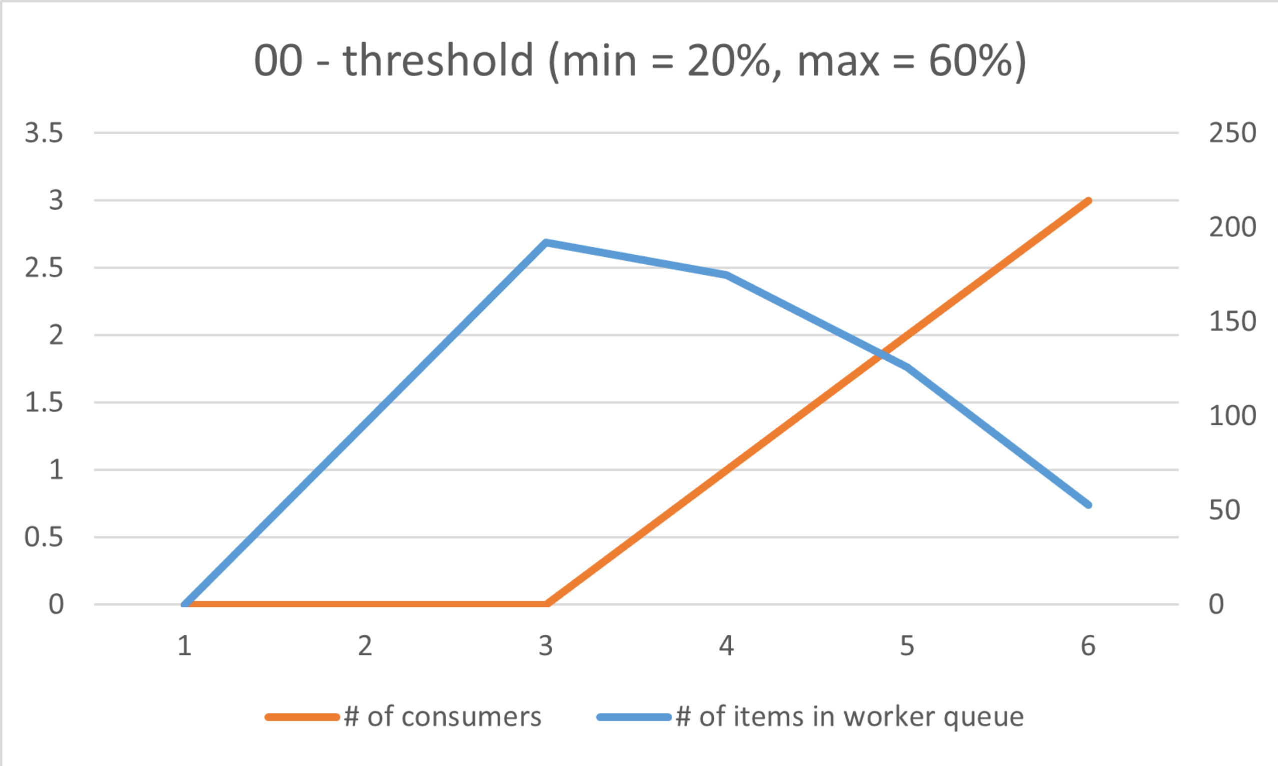
- **test 01 Runtime**

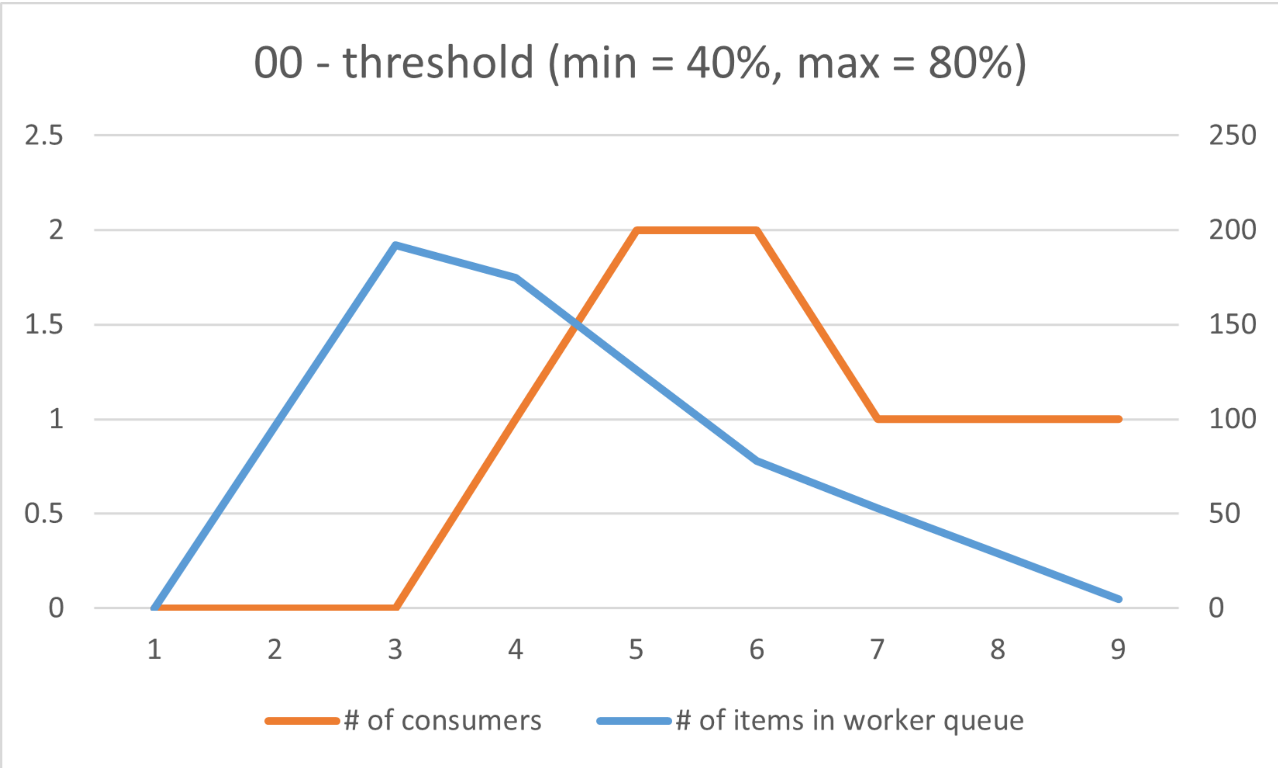
Threshold (min, max)	Runtime
(40%, 60%)	58.9171
(20%, 80%)	59.7507
(20%, 60%)	58.7007
(40%, 80%)	59.7340

- **test 00 Figures**

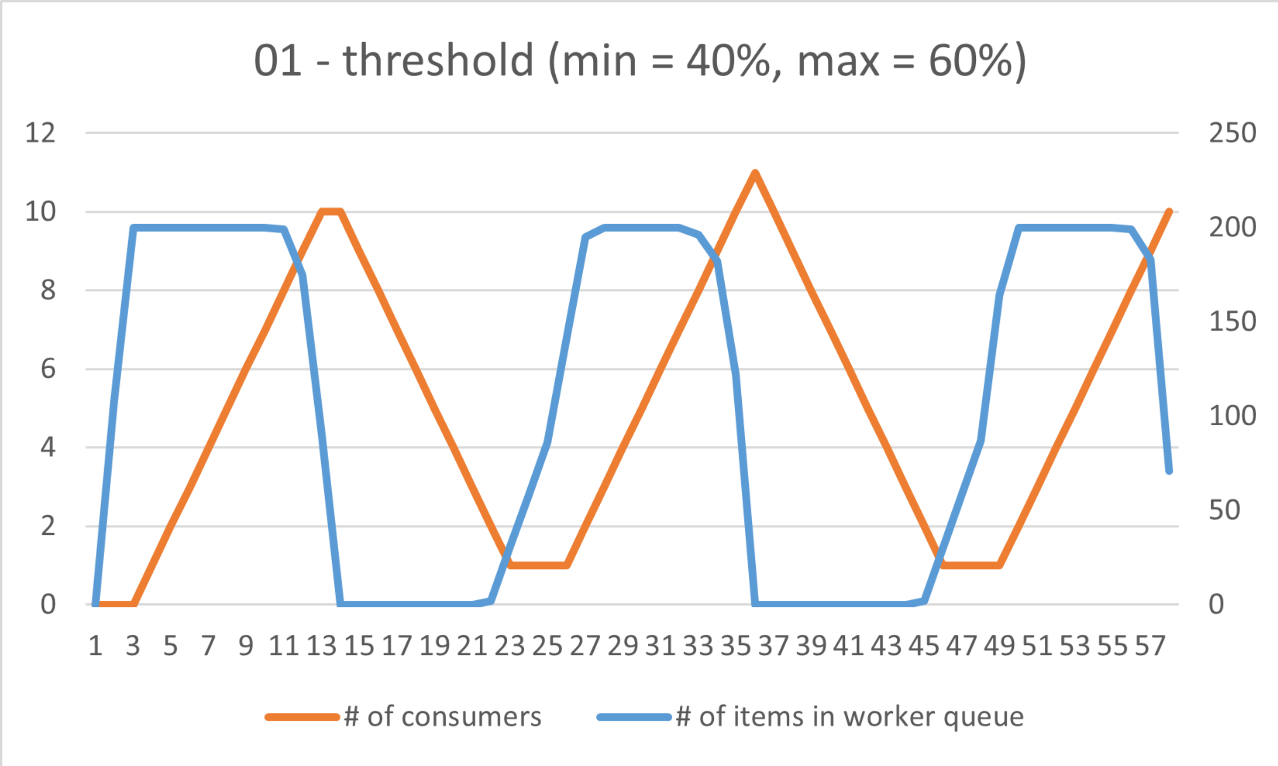

00 - threshold (min = 40%, max = 60%)
3.5
3
2.5
2
1.5
1
0.5
0
250
200
150
100
50
0
1
2
3
4
5
6
7
# of consumers
# of items in worker queue

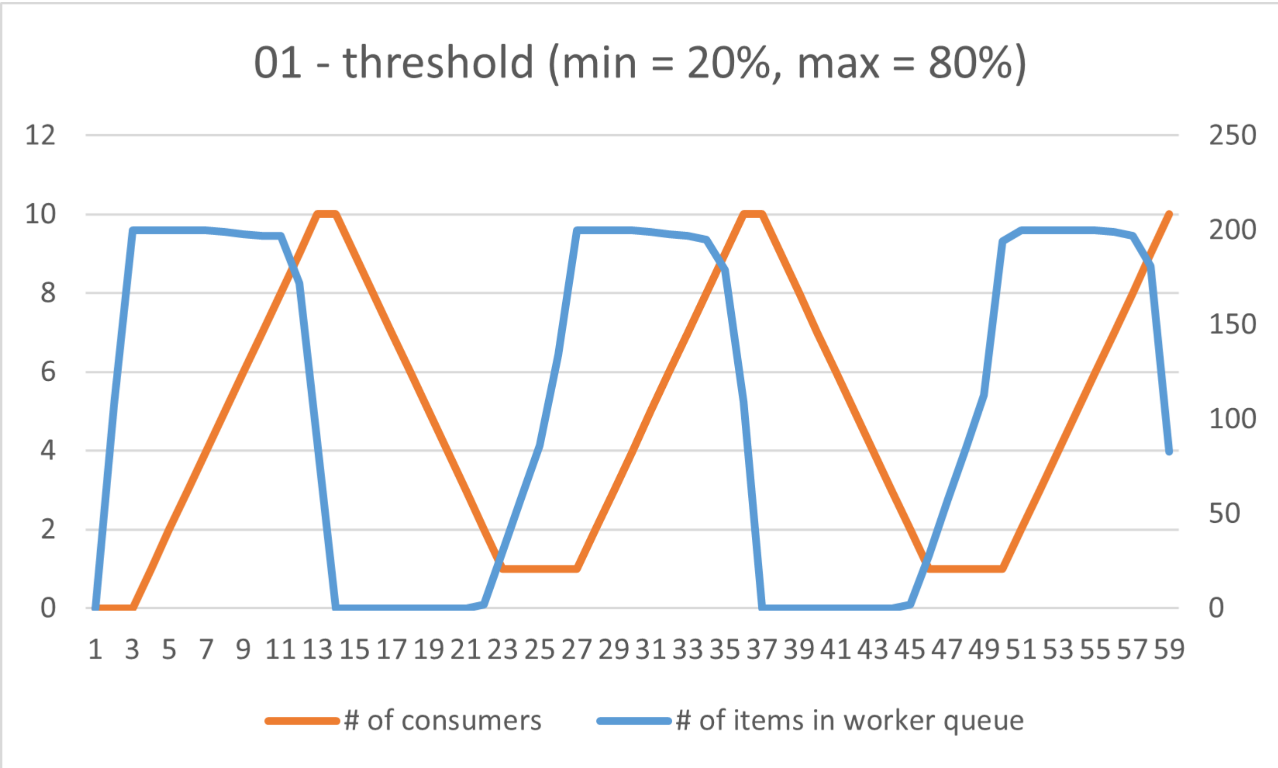

00 - threshold (min = 20%, max = 80%)
2.5
2
1.5
1
0.5
0
250
200
150
100
50
0
1
2
3
4
5
6
7
8
# of consumers
# of items in worker queue

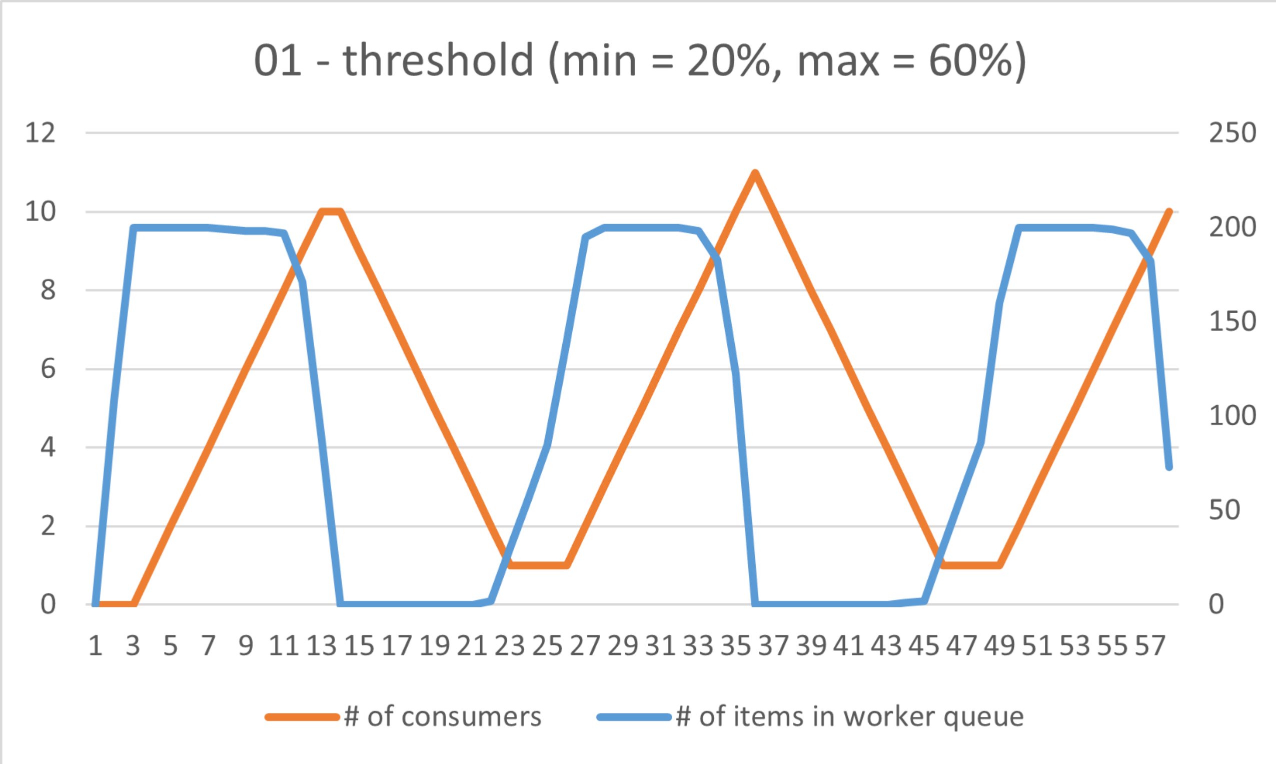


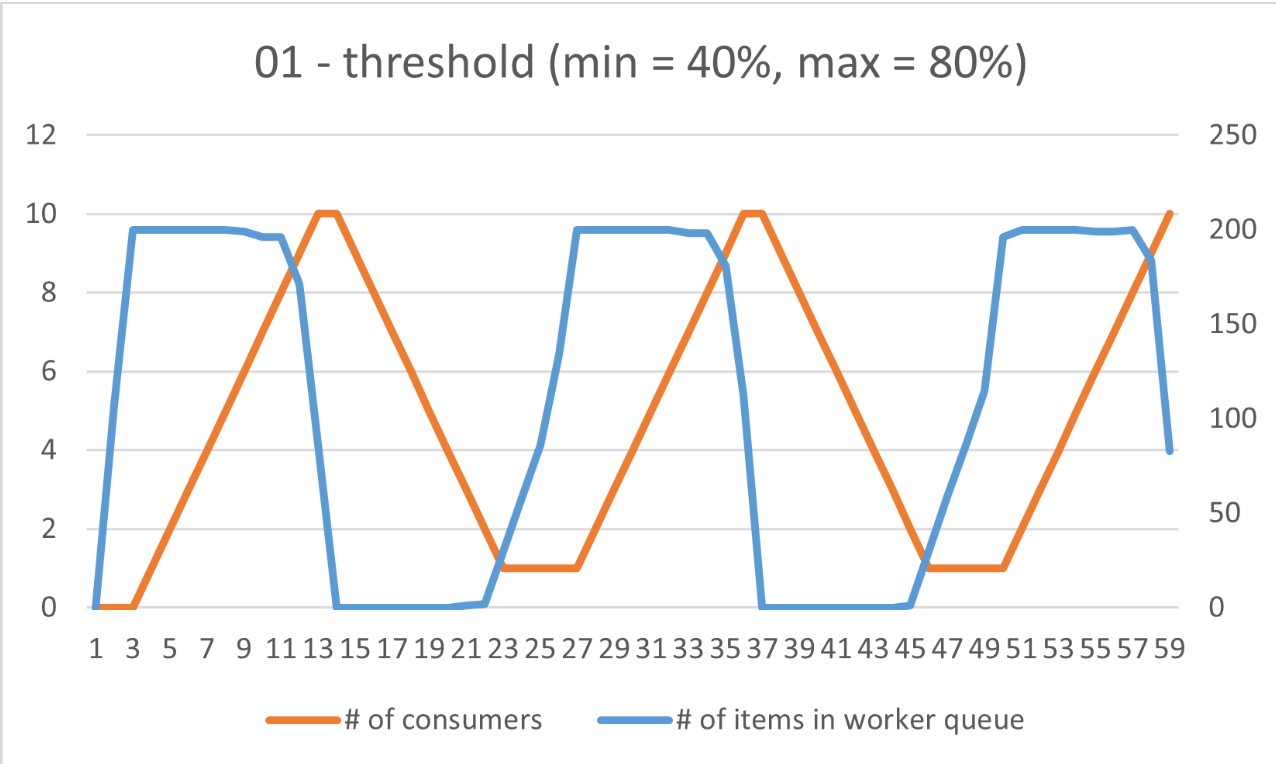


- **test 01 Figures**


01 - threshold (min = 40%, max = 60%)
0 2 4 6 8 10 12
0 50 100 150 200 250
1 3 5 7 9 11 13 15 17 19 21 23 25 27 29 31 33 35 37 39 41 43 45 47 49 51 53 55 57
# of consumers
# of items in worker queue


01 - threshold (min = 20%, max = 80%)
0 2 4 6 8 10 12
0 50 100 150 200 250
1 3 5 7 9 11 13 15 17 19 21 23 25 27 29 31 33 35 37 39 41 43 45 47 49 51 53 55 57 59
# of consumers
# of items in worker queue





Different values of WORKER_QUEUE_SIZE

Discussion

Worker queue size 設定的大一點，雖然能增加處理更多 items 的能力，但當 work queue size 太大的時候會導致 consumer controler 沒有創建 consumer 或是 consumer 數量增長延遲的情況。

Result

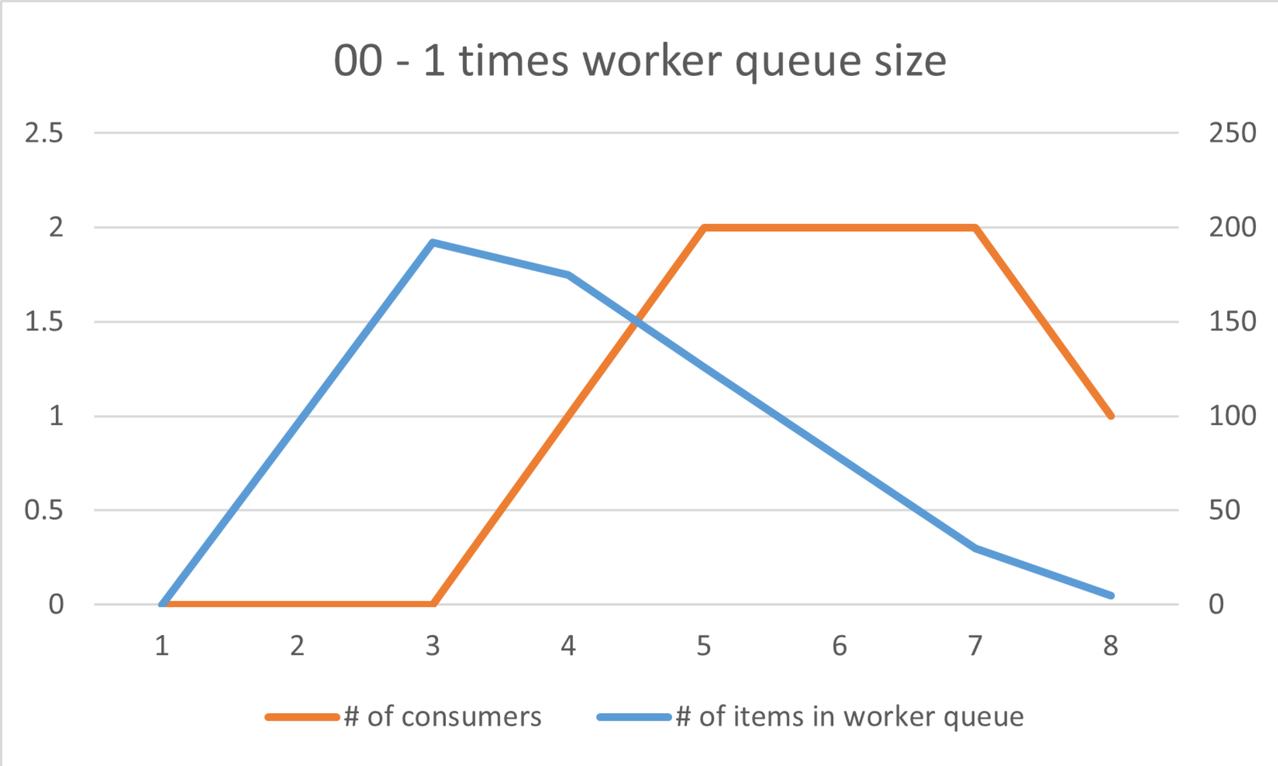
- **test 00 Runtime**

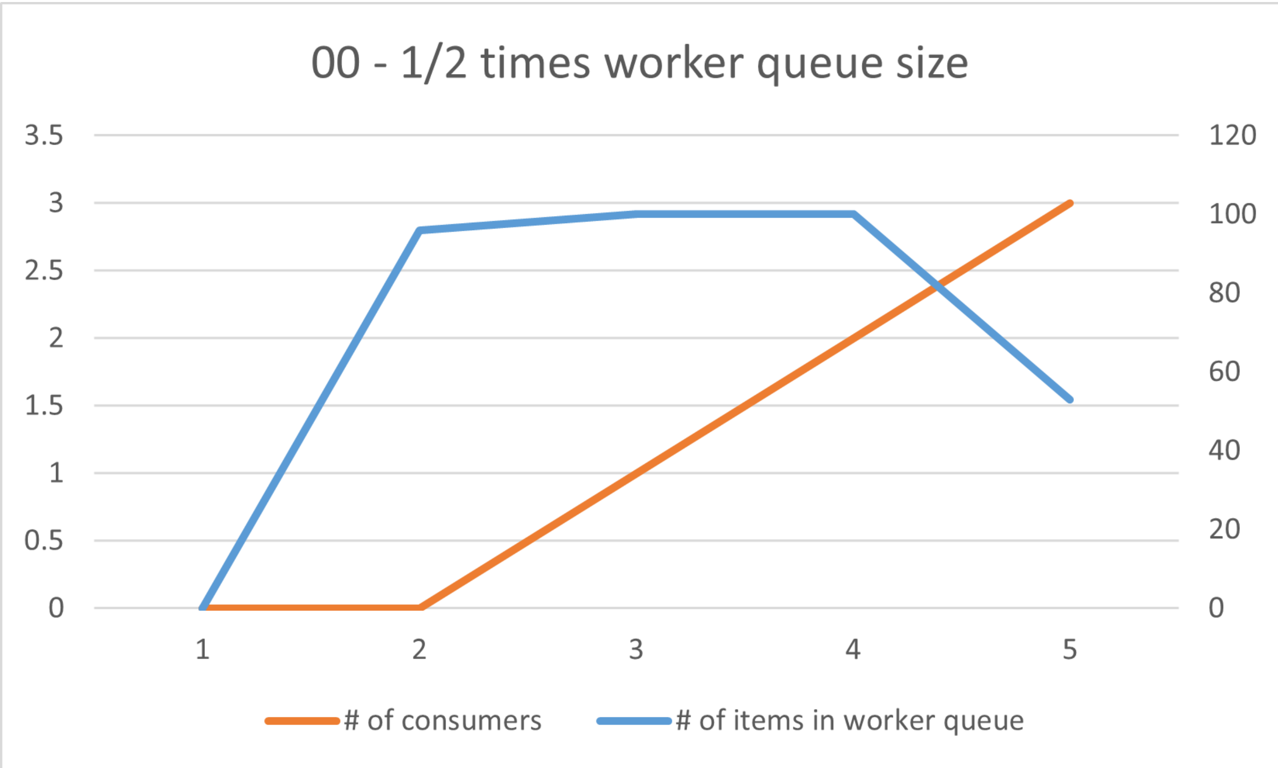
Work queue size	Runtime
2 times	Infinity (never end)
1 times	7.25883
1/2 times	4.77562

- **test 01 Runtime**

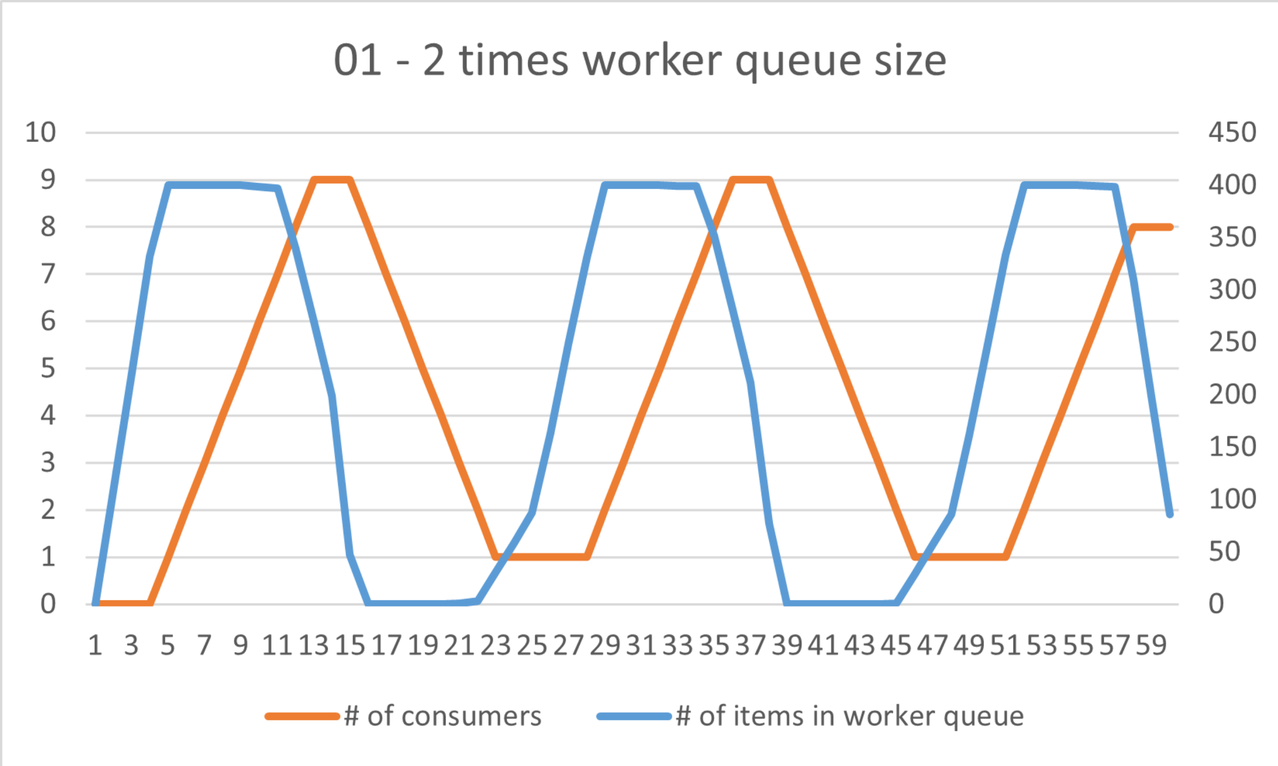
Work queue size	Runtime
2 times	60.4075
1 times	59.7507
1/2 times	56.7949

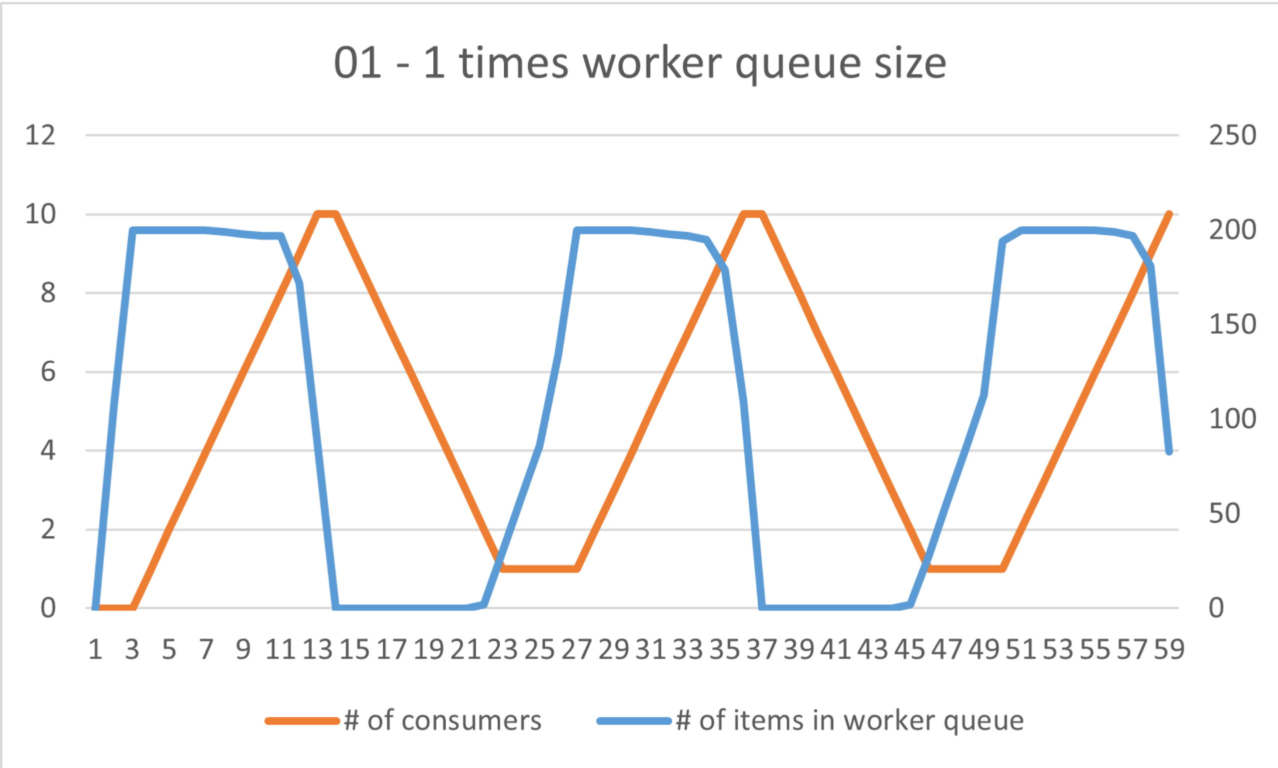
- **test 00 Figures**

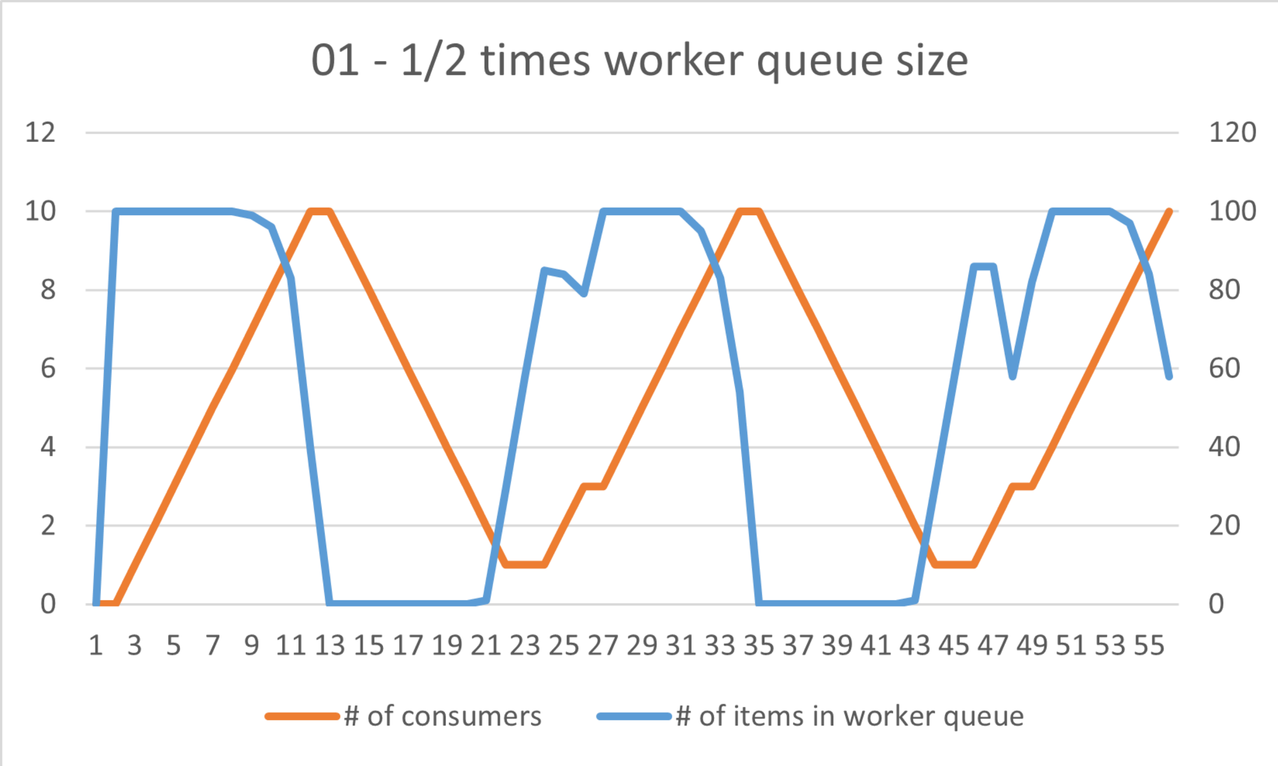




- **test 01 Figures**


01 - 2 times worker queue size
10
9
8
7
6
5
4
3
2
1
0
450
400
350
300
250
200
150
100
50
0
1 3 5 7 9 11 13 15 17 19 21 23 25 27 29 31 33 35 37 39 41 43 45 47 49 51 53 55 57 59
# of consumers
# of items in worker queue


01 - 1 times worker queue size
12
10
8
6
4
2
0
250
200
150
100
50
0
1 3 5 7 9 11 13 15 17 19 21 23 25 27 29 31 33 35 37 39 41 43 45 47 49 51 53 55 57 59
# of consumers
# of items in worker queue



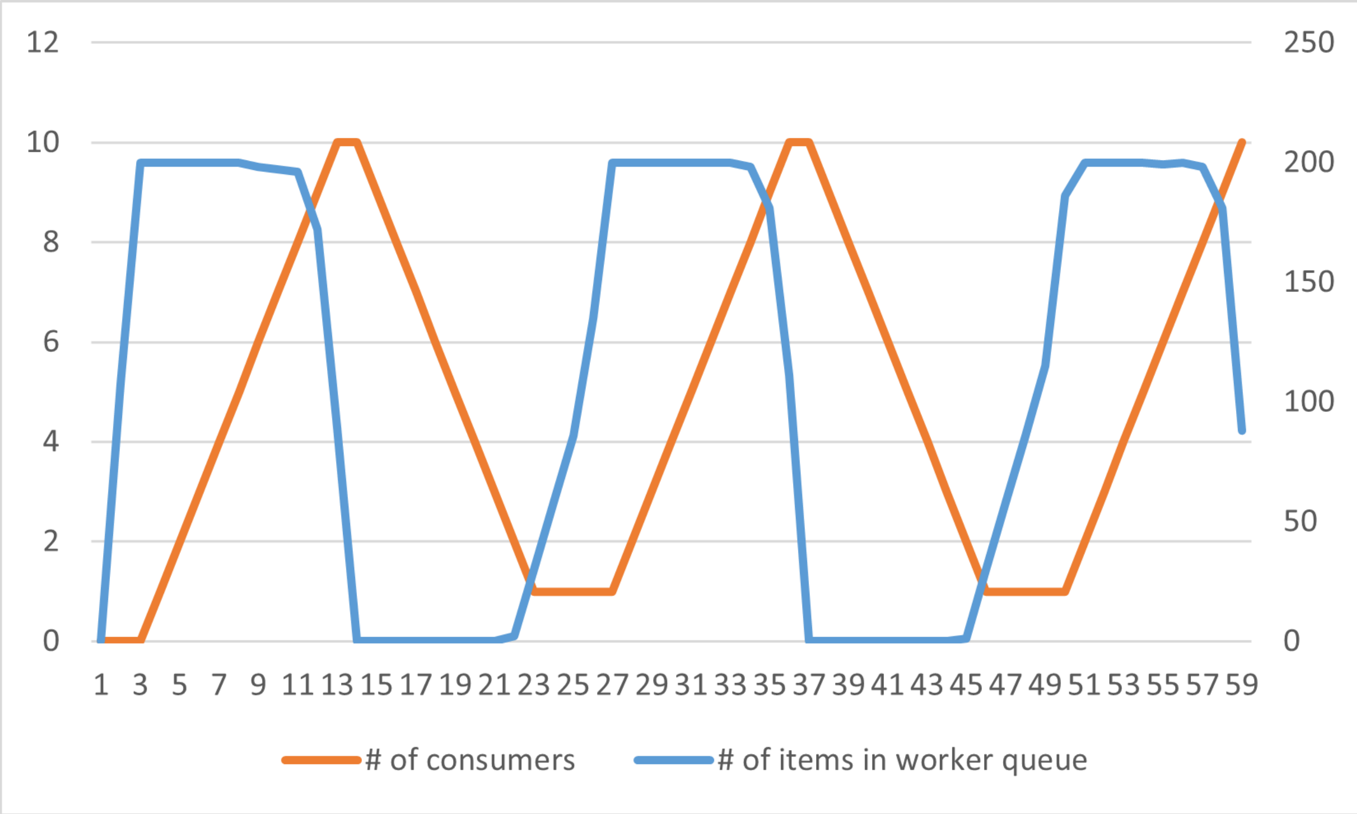
What happens if WRITER_QUEUE_SIZE is very small?

1/100 times original writer queue size

Discussion

The Consumer will frequently block while attempting to enqueue data into the output_queue when it becomes full. The Consumer will need to wait for the Writer to process data and free up space. It might becomes a bottleneck due to its small size, the overall throughput of the system will decrease.

Result



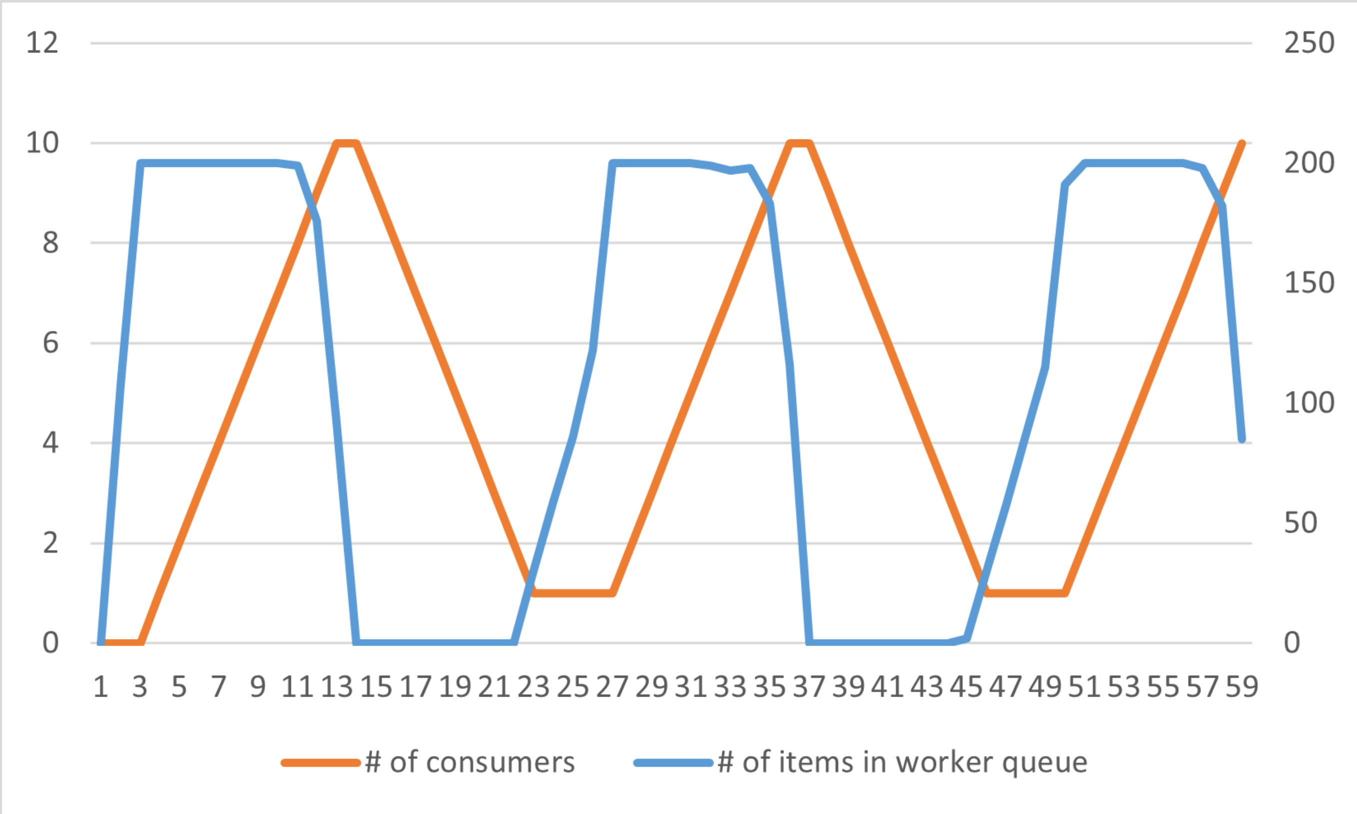
What happens if READER_QUEUE_SIZE is very small?

1/10 times original reader queue size

Discussion

The Reader will frequently block while attempting to enqueue data to the input_queue from the input source when it becomes full. It will need to wait for the Producer to process data and free up space. It might becomes a bottleneck due to its small size, the overall throughput of the system will decrease.

Result



What difficulties did you encounter when implementing this assignment?

At first, I was uncertain about when to shut down the Producers, Consumers and the Consumer Controller. Unlike the Reader and Writer, which have a specific number of tasks to complete, they don't have a clearly defined stopping point. Initially, I considered using a flag to indicate when the Reader had finished its job. This flag would allow the Producers to shut down once the input queue was empty. However, after discussing with my peers, we realized that this was unnecessary. The program will naturally terminate once both the reader and writer finish their tasks, ensuring that all threads, including the consumers, shut down properly.

Feedback

這份 Pthread 跟 MP4 有點像，因為描述得比較少的關係，一開始要怎麼做真的毫無頭緒，不過做完之後其實覺得不會很難，但就還是會擔心有沒有什麼東西不符合 spec 的要求。