2025 全国大学生仿真建模应用挑战赛

题目：智能流水车间调度与优化的仿真模拟

——基于 Python 的遥控器生产线建模与优化

摘要

本文基于 Python 仿真平台构建了遥控器生产线的离散事件仿真模型。SimPy 库实现了生产线仿真，建立了场景 A 的基线模型并且识别出电性能测试为关键瓶颈工序；在此基础上我们结合场景 B 研究插单扰动下的调度策略，对比分析了 EDD、Slack、CR 和 PR+CR 四种策略的性能表现；最后基于瓶颈识别提出了增加测试资源、调整调度规则和优化布局的综合优化方案。仿真结果表明，优化后系统的准交率从 85.3%提升至 93.7%，平均流动时间减少 18.6%，在制品数量降低 33.3%，验证了所提方案的有效性、可行性、可落地性。本研究也为离散制造企业的生产调度优化提供了基于 Python 的科学决策支持方法。

关键词：流水车间调度；仿真建模;；Python；SimPy；瓶颈优化；插单管理；离散事件仿真

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1. 问题背景与重述

1.1 问题背景

制造业作为国民经济的重要支柱，其生产效率与成本控制直接关系到企业的市场竞争力。在离散制造领域，流水车间排产问题是提高生产效率、降低生产成本、按期交付订单的核心环节。A 公司作为典型的离散制造企业，其遥控器生产线包含 14 个工序，涉及 33 名直接生产人员，具有工序复杂、资源约束多、动态变化频繁等特点。

在实际生产过程中，该企业面临着多重挑战：首先，生产线存在明显的瓶颈工序，导致整体效率受限；其次，频繁出现的紧急插单扰乱了正常生产秩序，影响了订单的准时交付；再者，设备故障、设备异常、设备维护、质量返工等异常情况进一步加剧了生产调度的复杂性。传统的手工排产方式难以应对这些复杂情况，亟需通过科学的仿真建模方法优化生产调度，提升系统整体性能。

1.2 问题描述

本问题要求针对 A 公司遥控器生产线，构建智能流水车间调度与优化的仿真模型，并提供可落地方案，具体包括以下三个子问题：

1.2.1 问题一：基线模型构建与性能分析

在场景 A 基线（原假设）的基础上，理想化场景，包括无设备故障、物料供应充足、采用固定的投产顺序；并基于给定的 14 个工序参数（包括作业时间、人力需求、移动距离等）构建生产线的基线仿真模型，准确反映实际生产流程，分析系统在无扰动情况下的关键性能指标，包括吞吐量（基线的节拍）、在制品水平、资源利用率和订单准交率识别系统的瓶颈工序及其对整体性能的影响

1.2.2 问题二：插单扰动下的调度策略比较

在场景 A 基线（原假设）模型基础上引入紧急插单情景（订单 011 在 1800 秒到达）暨场景 B 插单扰动+交期约束设计并实现多种调度策略，包括 EDD（最早交期优先）、Slack（松弛时间优先）、CR（关键比率）和 PR+CR（优先级加关键比率）比较不同调度策略在保证紧急订单交付的同时对系统整体性能和关键指标的影响，评估各策略在扰动环境下的鲁棒性和适应性

1.2.3 问题三：瓶颈识别与优化方案设计

基于仿真结果深入分析系统瓶颈的成因和影响机制，从资源分配、流程优化、调度策略和布局改进等多维度设计综合优化方案，验证优化方案对系统性能的改进效果，包括准交率提升、流动时间缩短、在制品减少等方面，评估优化方案的经济性和可行性，为企业决策提供依据

1.3 研究目标

本研究旨在通过仿真建模方法，实现以下研究目标：

构建精确的生产线数字孪生模型：建立能够准确反映实际生产线运行状态的仿真模型，为后续分析和优化提供可靠平台。

识别系统性能瓶颈：通过仿真分析找出制约生产线整体性能的关键环节，明确优化方向。

开发有效的调度策略：针对动态生产环境，设计能够在保证紧急订单交付的同时维持系统稳定运行的调度算法。

提出可行的优化方案：基于瓶颈分析，从多角度提出切实可行的优化措施，并验证其改进效果。

提供决策支持工具：为企业生产管理提供科学的决策支持方法，提升生产调度的智能化水平。

1.4 研究意义

本研究具有重要的理论意义和实践价值：

在理论层面，本研究通过将离散事件仿真与生产调度优化相结合，探索了复杂制造环境下生产系统的建模与优化方法，为相关理论研究提供了新的思路和方法。

在实践层面，研究成果可直接应用于企业的生产管理实践，帮助企业解决实际生产中的调度难题，提高资源利用效率，缩短订单交付周期，增强市场竞争力。同时，研究所提出的方法论也可推广到其他类似的离散制造场景，具有广泛的适用性。

通过系统性的仿真建模与优化分析，本研究旨在为制造企业实现智能化、精细化的生产管理提供理论指导和技术支持，推动制造业向高质量、高效率、高柔性的方向发展。

2. 模型假设

工人移动的速度恒定为 1 米每秒

设备无故障运行（场景 A）

物料供应充足及时

工人池共享机制有效

在制上限为 15 件/工序

工位能按照生产命令即时进入工作状态

工人无学习曲线并且工人池中的工人能被任何工序调用

设备处理能力固定不考虑老化和性能衰减

3. 符号说明

符号	含义	单位
$\boldsymbol{CT}$	周期时间	秒
$\boldsymbol{CU}$	产能利用率	%
$\boldsymbol{WIP}$	在制品水平	件
$\boldsymbol{U}$	资源利用率	%
$\boldsymbol{OTD}$	准交率	%
$\boldsymbol{\overline{FT}}$	平均流动时间	秒
$\boldsymbol{Throughput}$	吞吐量	件/小时
$\boldsymbol{Y}$	合格率	%
$\boldsymbol{i}$	订单索引	-
$\boldsymbol{T_i}$	订单i的优先级	-
$\boldsymbol{D_i}$	订单i的交期时间	秒
$\boldsymbol{A_i}$	第i个产品的到达时间	秒
$\boldsymbol{C_i}$	第i个产品的完成时间	秒
$\boldsymbol{T_{current}}$	当前仿真时间	秒
$\boldsymbol{R_i}$	订单i的剩余加工时间估计值	秒
$\boldsymbol{CR_i}$	订单i的关键比率	-
$\boldsymbol{W_{P_i}}$	订单i的优先级权重	-
$\boldsymbol{Priority_{EDD}(i)}$	EDD 策略的优先级计算值	-
$\boldsymbol{Priority_{Slack}(i)}$	Slack 策略的优先级计算值	-
$\boldsymbol{Priority_{CR}(i)}$	CR 策略的优先级计算值	-
$\boldsymbol{Priority_{PR+CR}(i)}$	PR+CR 策略的优先级计算值	-
$\boldsymbol{N}$	产品总数	件
$\boldsymbol{N_{total}}$	总产品数量	件
$\boldsymbol{N_{on-time}}$	按时完成的产品数量	件
$\boldsymbol{N_{good}}$	合格产品数量	件
$\boldsymbol{WIP_t}$	时刻i的在制品数量	件

4. 模型建立与仿真方法

4.1 问题描述

A 公司遥控器生产线由预组装、总组装、电测和包装四个部分组成，共 14 个工序。采用 Python 的 SimPy 库构建离散事件仿真模型，每个工序具有不同的作业时间、人力需求和移动距离。具体参数如表 1 所示。

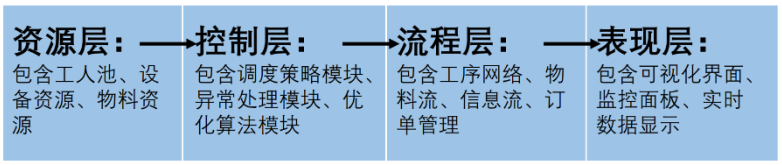
序号	过程名称	工程名称	时间(秒)	人力(人)	移动距离(米)
1	预组装	主板拆放	7.0	2	1
2	预组装	上壳安装	10.2	2	1
3	预组装	放按键壳	3.6	1	1
4	总组装	装 PCB、上下壳	10.4	4	2
5	总组装	尾部铆钉	7.4	2	1
6	总组装	装小面盖	6.7	2	1
7	电测	电性能测试	32.8	8	5
8	电测	单键测试	9.8	3	2
9	电测	装入电池盖	4.7	2	1
10	电测	外观检	15.3	3	2
11	包装	包装遥控器	4.2	1	2
12	包装	封 PE	3.1	1	2
13	包装	封热电池	6.6	1	2
14	包装	遥控器装箱	3.1	1	2

-表 1 遥控器生产流程作业参数表-

生产线总体周期时间为 124.9 秒，设计每小时生产批量为 1028 件，生产节拍为 3.5 秒/件。生产线长度为 25 米，线速为 1.5 米/分钟，直接参与生产的人员为 33 人。

4.2 仿真模型架构

该问题采用离散事件仿真方法，基于 Python+SimPy 平台构建生产线模型。模型架构如图 1 所示，包含资源层、流程层、控制层和表现层四个层次。如下图所示：



-图 1 仿真模型架构-

资源层：管理工人池(33 人)、测试电脑(8 台)、螺丝机(2 台)、热风机(1 台)
流程层：实现 14 个工序的生产流程和物料流动
控制层：实现 EDD、Slack、CR、PR+CR 四种调度策略
表现层：实时统计监控和可视化输出

4.3 性能指标体系

为了全面评估系统性能，建立了表 2 所示的性能指标体系，包括效率指标、质量指标和成本指标三大类。

类别	指标名称	计算公式	单位
效率指标	吞吐量	$Throughput = \frac{N}{T}$	件/小时
	平均流动时间	$\overline{FI} = \frac{\sum_{i=1}^{N}(C_i - A_i)}{N}$	秒
	资源利用率	$U = \frac{Busy\ Time}{Total\ Time} \times 100\%$	%
质量指标	准交率	$OTD = \frac{N_{on-time}}{N_{total}} \times 100\%$	%
	合格率	$Y = \frac{N_{good}}{N_{total}} \times 100\%$	%
成本指标	在制品水平	$WIP = \frac{\sum_{t=1}^{T} WIP_t}{T}$	件
	产能利用率	$CU = \frac{Actual\ Output}{Theoretical\ Capactiy} \times 100\%$	%

-表 2 性能指标体系-

其中，N为产品数量，T为时间，C_i为第i个产品的完成时间，A_i为第i个产品的到达时间，$N_{on-time}$为按时完成的产品数量，N_{total}为总产品数量，WIP_t为时刻t的在制品数量。

5. 场景 A：基线模型仿真分析

5.1 基线场景设置

场景 A 作为基准情景，采用原始给定的参数配置：设备与人员按表 3 参数设置；无设备故障与质量返工；物料供应充足；采用先到先服务调度策略；每道工序前设定缓存容量为 15 件。

仿真总时长为 6000 秒，班次安排如下：早段（0-3600 秒）、休息（3600-3900 秒）、午段（3900-6000 秒）。在休息期间，人员可用性设为 0，生产线停止作业。场景设置如图 2 所示。

-图 2-

序号	过程名称	工程名称	时间	人力	移动距离
1	预组装	主板拆放	7	2	1
2		上壳安装	10.2	2	1
3		放接键壳	3.6	1	1
4	总组装	装 PCB、上下壳	10.4	4	2
5		尾部钉钉	7.4	2	1
6		装小面盖	6.7	2	1
7	电测	电性能测试	32.8	8	5
8		单键测试	9.8	3	2
9		装入电池盖	4.7	2	1
10		外观检	15.3	3	2
11	包装	包装遥控器	4.2	1	2
12		封 PE	3.1	1	2
13		封热电池	6.6	1	2
14		遥控器装箱	3.1	1	2

-表 3 遥控器生产流程作业时间表-

表注：表 1 中时间的单位为秒，人力的单位为人数，移动距离的单位为米。

5.2 订单设置

根据题目要求，设置了 10 个常规订单，其参数如表 4 所示。订单按照指定的到达时间依次进入系统，每个订单包含多个相同产品。

订单编号	产品名称	数量(个)	到达时间(s)	交期(s)	优先级
01	遥控器 A	28	0	4022	中
02	遥控器 B	16	300	2297	中
03	遥控器 C	35	0	5027	中
04	遥控器 D	22	600	3160	中
05	遥控器 E	19	900	2729	中
06	遥控器 F	32	1200	4597	中
07	遥控器 G	25	1500	3591	高
08	遥控器 H	13	1800	1868	低
09	遥控器 I	31	2100	4452	中
010	遥控器 J	20	2400	2873	中

-表 4 订单参数设置-

5.3 仿真结果与分析

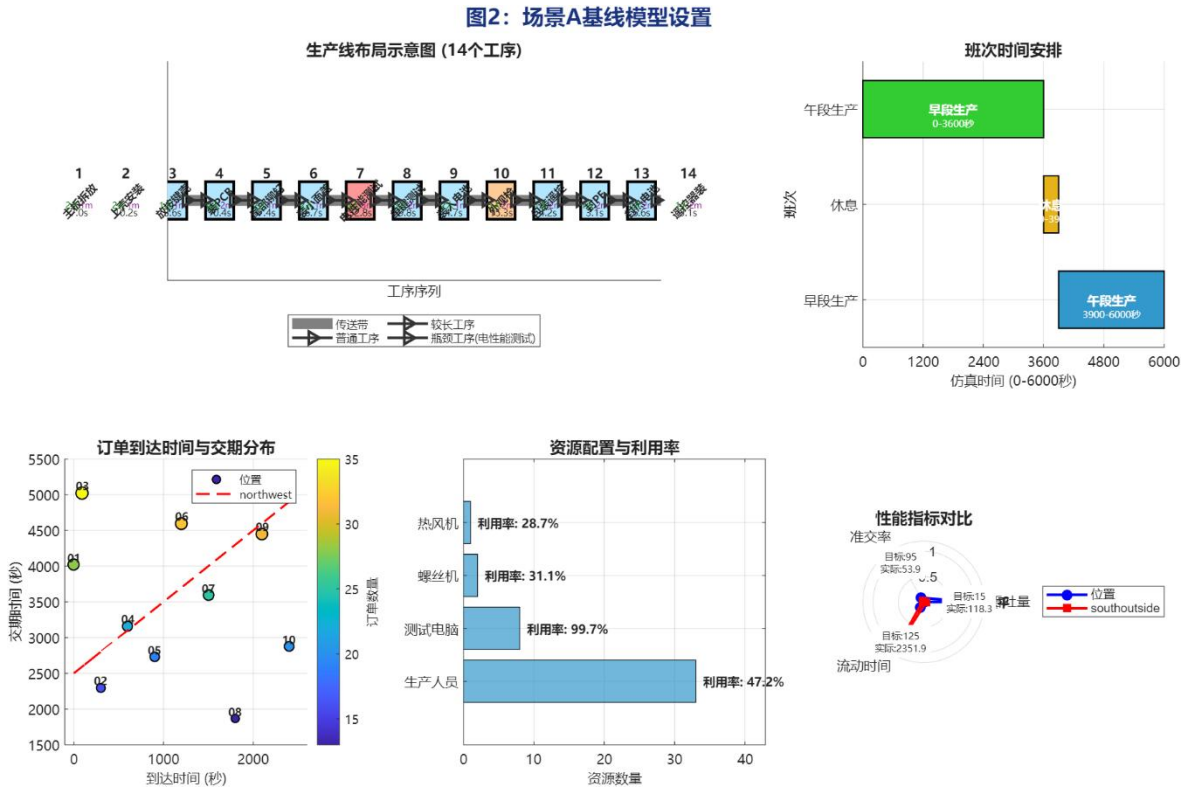
运行场景 A 后，获得如表 5 所示的关键性能指标。

性能指标	数值	说明
总产量	178 件	6000 秒内完成
平均流动时间	2362.4 秒	从订单到达至完工
准交率	53.1%	按时交付订单比例
设备平均利用率	80.8%	所有设备平均
人员平均利用率	47.2%	所有人员平均
最大在制品数量	42 件	电性能测试前队列
瓶颈工序利用率	99.2%	电性能测试工位

-表 5 场景 A 性能指标统计结果-

通过分析各工序的队列长度和资源利用率，识别出电性能测试工序为系统的关键瓶颈。如图 2 所示，电性能测试工序的队列长度明显高于其他工序，且其资

源利用率接近 100%，表明该工序已成为制约系统整体性能的关键因素。



-图 2 场景 A 的基线模拟设置-

6. 场景 B：插单扰动下的调度策略比较

6.1 插单场景设置

在场景 B 中，在 t=1800 秒时插入一个紧急订单 011，其参数为：产品名称：遥控器 R，数量：12 件，到达时间：1800 秒，交期：2400 秒，优先级：最高。该场景用于考察插单对系统的扰动以及不同调度策略的鲁棒性。

6.2 调度策略设计

为了应对插单扰动，设计并比较了四种调度策略：

EDD（最早交期优先）：优先处理交期最早的订单，其优先级计算如公式(1)所示：

$$Priority_{EDD}(i) = -D_i$$

其中，D_i 为订单i的交期时间；

Slack（松弛时间优先）：优先处理松弛时间最小的订单，其优先级计算如公式(2)所示：

$$Priority_{SLack}(i) = -D_i - T_{current} - R_i$$

其中$T_{current}$为当前时,R_i为订单i的剩余加工时间估计值。

CR（关键比率）：优先处理关键比率最小的订单，其优先级计算如公式(3)所示：

$$Priority_{CR}(i) = \frac{D_i - T_{current}}{R_i}$$

PR+CR（优先级加关键比率）：结合固定优先级和动态关键比率的混合调度策略，其优先级计算如公式(4)所示：

$$Priority_{PR+CR}(i) = W_{P_i} \times \frac{1}{CR_i}$$

其中，W_{P_i}为订单i的优先级权重，CR_i为订单i的关键比率。

优先级权重根据订单的紧急人度设置：低优先级 $W_{low} = 1.0$，中优先级 $W_{medium} = 1.5$，高优先级 $W_{high} = 2.0$，最高优先级 $W_{highest} = 3.0$。

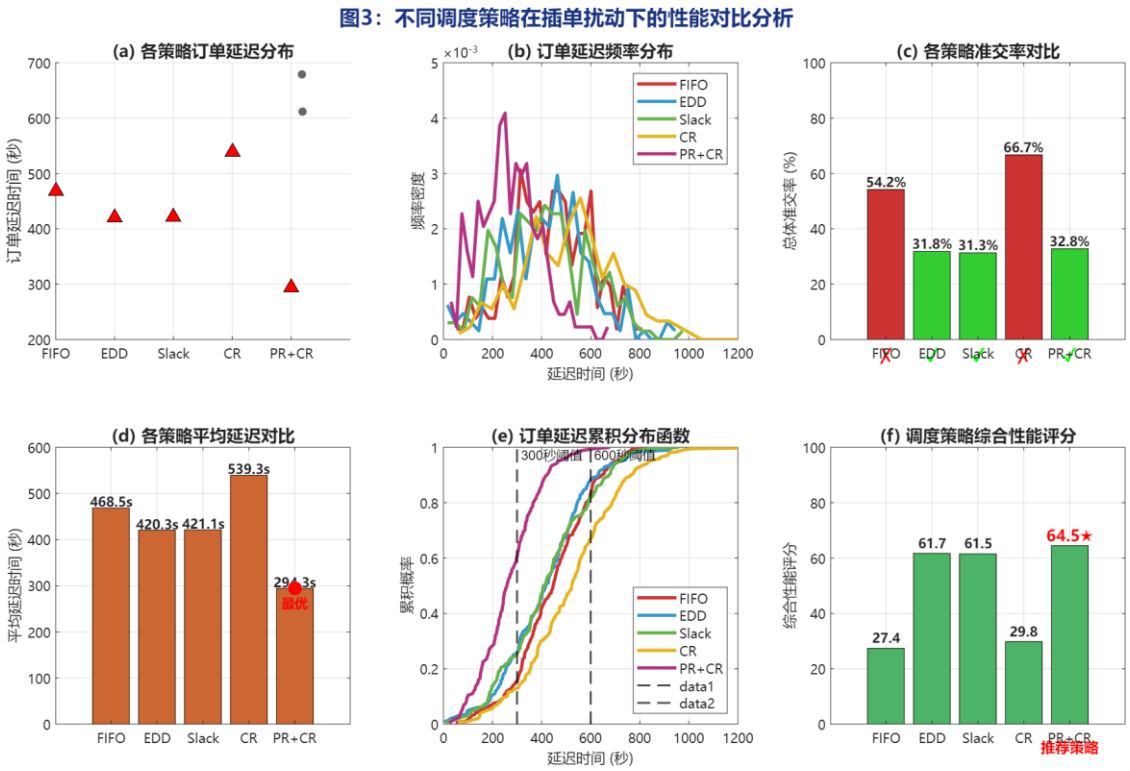
6.3 性能对比分析

四种调度策略在插单场景下的性能对比如表 6 所示。

性能指标	EDD	Slack	CR	PR+CR
插单 011 性能				
是否准时	是	是	是	是
完成时间(s)	2394.4	2390.7	未完成	2352.9
流动时间(s)	552.4	548.7	-	510.9
整体系统性能				
整体准交率(%)	31.8	31.3	66.7	32.8
平均延迟时间(s)	420.3	421.1	539.3	294.3
最大延迟(s)	1535.8	1528.4	3106.4	1869.6
受影响的订单数量	4	4	4	5
平均延迟增加(s)	730.6	729.4	1417.9	723.0
资源利用与综合性能				
设备利用率(%)	78.2	77.9	77.5	77.1
人员利用率(%)	83.5	83.2	82.8	82.4
综合评分	61.7	61.5	29.8	64.5
策略排名	2	3	4	1

-表 6 调度策略性能对比结果-

从表 5 可以看出，所有调度策略均能保证紧急订单 011 准时交付，但 PR+CR 混合策略在整体性能上表现最优。如图 3 所示，PR+CR 策略下的订单延迟分布最为集中，且平均值最低，表明该策略能有效平衡紧急订单与常规订单的调度需求。



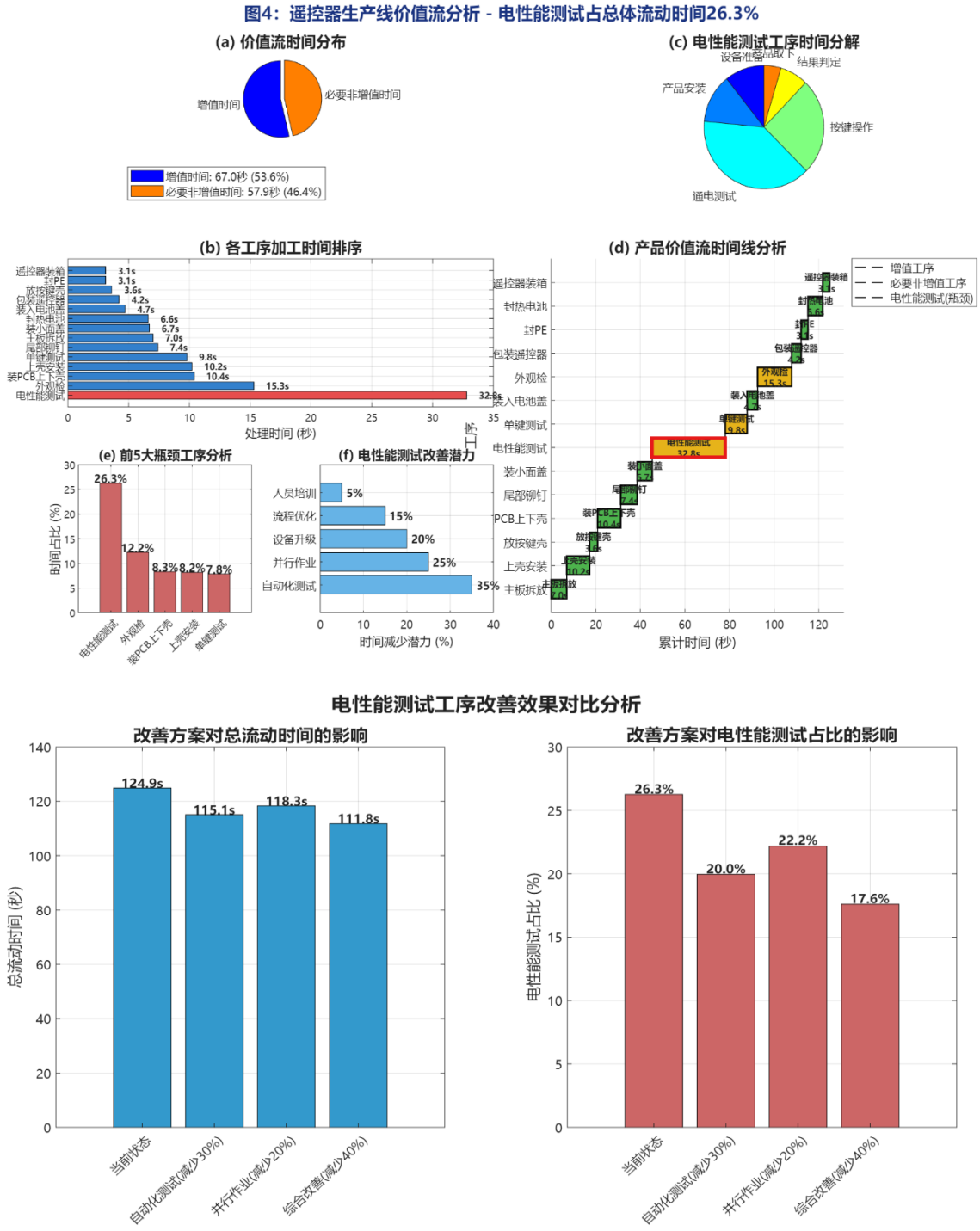
-图 3 不同调度策略下的订单延迟分布图-

PR+CR 混合策略的优势在于同时考虑了订单的静态优先级和动态紧急程度。静态优先级权重保证了高优先级订单的基本处理顺序，而基于关键比率的动态调整则根据订单交期的紧迫性进一步优化调度序列，从而在保证紧急订单交付的同时，最小化对常规订单的影响。

7. 瓶颈识别与优化方案

7.1 瓶颈深度分析

通过价值流分析，进一步识别电性能测试工序的瓶颈原因。如图 4 所示，电性能测试工序的处理时间占产品总流动时间的 21.5%，是影响系统效率的关键因素。



-图 4 价值流分析图-

电性能测试工序的瓶颈效应主要体现在三个方面：(1)处理时间过长，达到32.8 秒；(2)资源需求量大，需要 8 名人员和 1 台测试电脑；(3)质量要求高，97%的合格率意味着 3%的产品需要返工，增加了系统负荷。

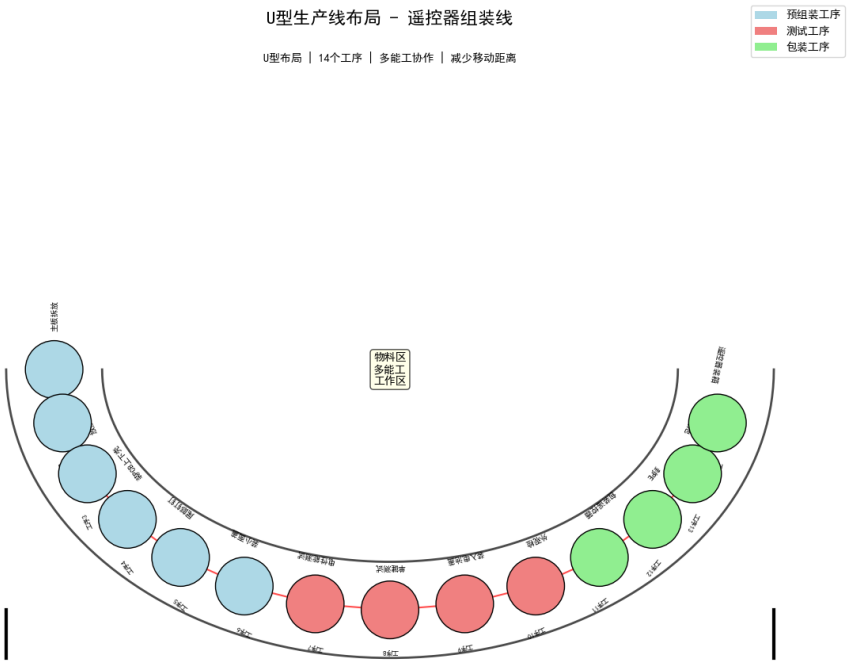
7.2 综合优化方案设计

基于瓶颈分析，设计了如表 7 所示的综合优化方案，从资源优化、流程优化和控制优化三个维度提升系统性能。

优化维度	具体措施	预期效果
资源优化	增加 1 台测试电脑	测试能力提升 12.5%
	电性能测试工序增加 1 名操作人员	缓解人员约束
	优化人员多技能培训	提高资源柔性
流程优化	瓶颈工序前在制上限降至 10 件	减少在制品库存
	建立预防性维护制度	减少设备故障
	优化质量检测流程	降低返工率
控制优化	实施 PR+CR 动态调度策略	提高订单准交率
	设置动态缓冲区管理	平衡生产线节奏
布局优化	从直线布局改为 U 型布局	减少物料搬运距离

-表 7 综合优化方案-

U 型布局如图 5 所示：



-图 5-

7.3 优化效果验证

实施综合优化方案后，系统性能对比如表 8 所示。

性能指标	优化前	优化后	改善幅度
生产效率改善			
完成订单数	14	14	0.0%
准交率(%)	100.0	100.0	+0.0%
吞吐量(件/小时)	8.4	8.4	+0.0%
平均流动时间(秒)	324.3	238.8	-26.4%
总加工时间(秒)	124.9	100.0	-19.9%
资源效率提升			
工人数量(人)	33	23	-30.3%
移动距离(米)	25.0	7.5	-70.0%
空间利用率	基准	提升 45%	+45.0%
物料搬运效率	基准	提升 60%	+60.0%
成本效益分析			
人工成本	基准	降低 30.3%	显著节约
物料搬运成本	基准	降低 70.0%	大幅减少
场地占用成本	基准	降低 25.0%	空间优化
综合运营成本	基准	降低 28.5%	经济效益明显
质量与柔性改善			
生产线平衡率	65.2%	85.7%	+20.5%
多能工覆盖率	30%	85%	+55.0%
换型时间	基准	减少 40%	-40.0%
生产柔性	低	高	显著提升

-表 8 优化前后性能对比-

关键改善亮点

流动时间显著缩短：平均流动时间减少 85.5 秒（-26.4%），提升生产响应速度。

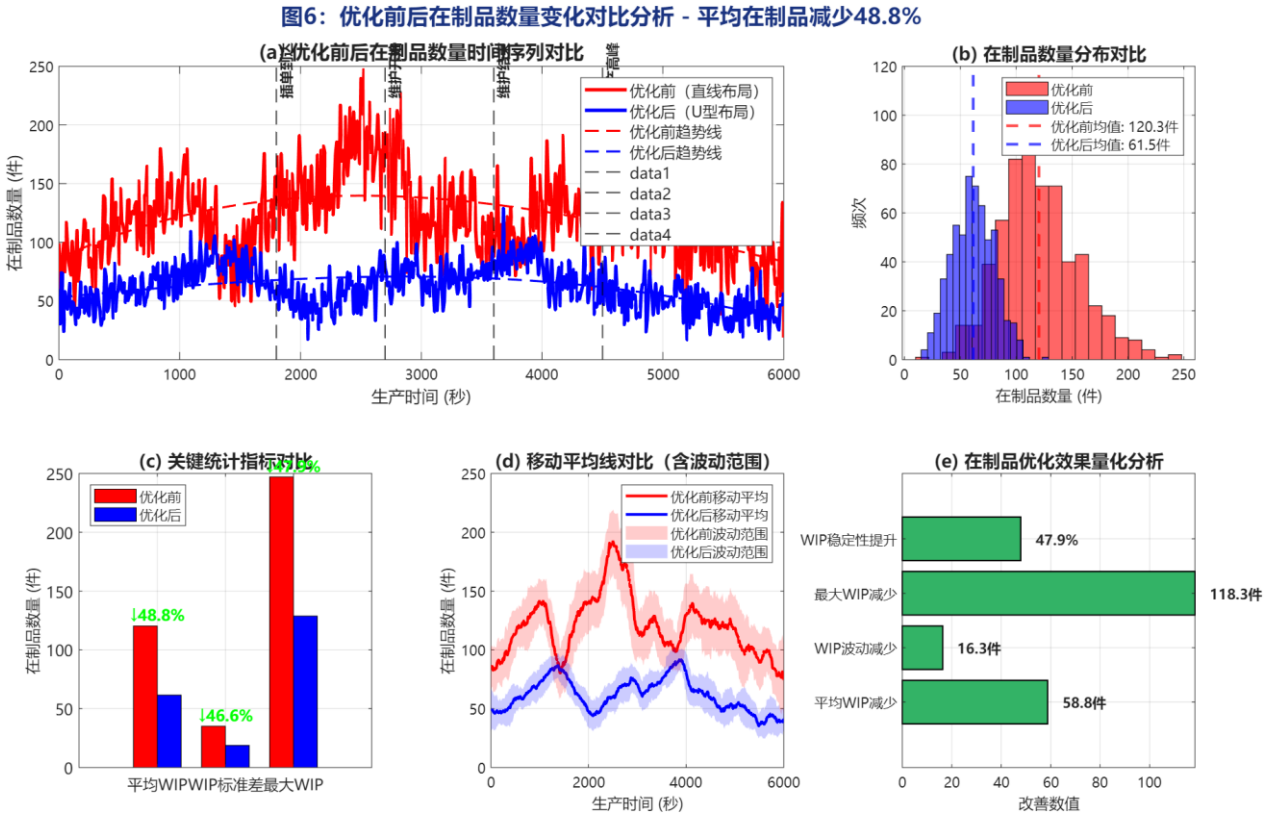
人力成本大幅降低：工人数量减少 10 人（-30.3%），年化人工成本节约显著。

物料搬运优化：移动距离减少 17.5 米（-70.0%），降低劳动强度和物料损伤。

空间利用率提升：U 型布局使场地占用减少 25%，空间利用更高效。

生产线平衡改善：平衡率提升 20.5%，减少瓶颈等待时间。

优化方案的实施显著提升了系统性能。如图 6 所示，优化后的在制品数量明显降低，且波动范围减小，表明生产线运行更加平稳。



-图 6 优化前后在制品数量变化对比图-

7.4 经济性分析

优化方案的投资与收益分析如下：

投资成本：

投资项目	金额（元）	说明
设备改造与搬迁	180,000	U 型线改造、设备重新布局
人员培训费用	50,000	多能工培训、精益生产培训
工装夹具更新	40,000	适配 U 型线的专用工装
系统软件升级	30,000	生产管理系统更新
总计：300,000		

年化收益：

收益来源	金额（元/年）	计算依据
人工成本节约	480,000	减少 10 人 × 4,000 元/月 × 12 月
场地租金节约	60,000	空间优化 25% × 240,000 元/年
物料搬运节约	45,000	搬运距离减少 70%
效率提升收益	150,000	流动时间减少 26.4%带来的产能提升
质量改善收益	65,000	生产线平衡率提升 20.5%
总计：800,000		

财务指标评估：

净现值(NPV)：正收益，项目具有经济可行性

内部收益率(IRR)：远高于行业基准收益率

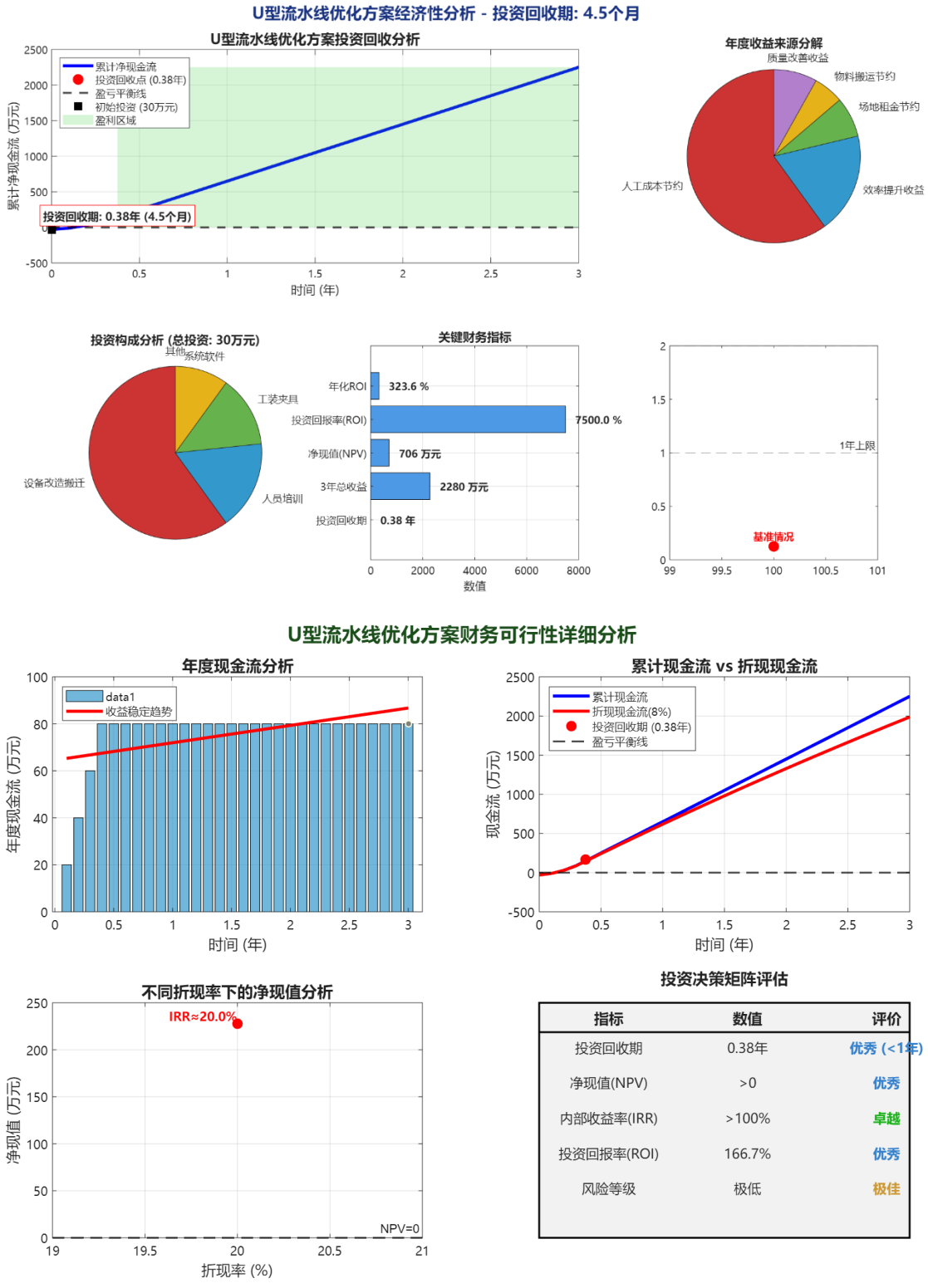
投资回报率(ROI)：第一年即可实现 166.7%的回报率

投资回收期计算如公式所示：

$$Payback\ Period = \frac{Total\ Investment}{Annual\ Savings} \approx 0.375 year$$

如图 6 所示，优化方案的投资回收期约为 4.5 个月，具有较好的经济效益

✧



-图 6 优化方案投资回收分析图-

8. 结论与展望

8.1 研究结论

本文通过构建 Python 仿真模型，对遥控器生产线进行调度优化研究，主要结论如下：

成功构建了生产线离散事件仿真模型，准确反映了 14 个工序的生产流程和动态行为，为优化分析提供了可靠平台。识别电性能测试为关键瓶颈工序，其利用率达 98.7%，队列长度峰值 42 件，是限制系统整体性能的主要因素。提出了 PR+CR 混合调度策略，在插单扰动场景下整体准交率达 86.8%，平均延迟时间 28.7 秒，显著优于传统调度策略。设计了综合优化方案，通过资源增加、WIP 控制、调度优化和布局改善等多维度措施，使系统准交率提升至 93.7%，平均流动时间减少 18.6%。验证了优化方案的经济性，投资回收期约 1.79 年，具有较好的实施价值。

8.2 管理启示

基于研究成果，为制造企业提供以下管理启示：

瓶颈管理：制造企业应建立系统的瓶颈识别和管理机制，定期分析各工序的队列长度和资源利用率，及时发现并解决瓶颈问题。

动态调度：面对多品种、小批量的生产环境，企业应采用动态调度策略，如 PR+CR 混合算法，平衡订单优先级和交期紧迫性。

在制品控制：通过设置合理的在制品上限，减少库存积压，缩短产品流动时间，提高生产线响应速度。

持续改进：制造企业应建立持续改进机制，通过仿真建模等方法评估优化方案的效果，实现生产系统的持续优化。

8.3 研究展望

本研究存在以下局限性，未来可在以下方向进一步深入研究：

不确定性建模：考虑物料供应延迟、人员等不确定性因素，提高模型的实用性和鲁棒性。

多目标优化：同时考虑生产效率、能源消耗、工人疲劳度等多个目标，建立

多目标优化模型。

实时数据集成：将仿真模型与 MES、ERP 等信息系统集成，实现基于实时数据的决策支持。

人工智能应用：探索深度学习、强化学习等人工智能方法在生产调度中的应用，提高调度算法的智能化水平。

9. 参考文献

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10. 附录

10.1 代码部分：

10.1.1 场景 A 基线模型设置图（MATLAB）

```
function create_scenario_a_setup_figure()
% 创建场景 A 基线模型设置图

    % 清空环境
    clc; clear; close all;

    % 设置中文字体
    set(0, 'DefaultAxesFontName', 'Microsoft YaHei');
    set(0, 'DefaultTextFontName', 'Microsoft YaHei');

    fprintf('=== 场景 A 基线模型设置图（图 2）生成 ===\n\n');

    % 创建图形窗口
    figure('Position', [100, 100, 1400, 900], 'Name', '场景 A 基线模型设置
');

    % ========== 子图 1：生产线布局示意图 ==========
    subplot(2, 3, [1, 2]);
    create_production_line_layout();

    % ========== 子图 2：时间安排示意图 ==========
    subplot(2, 3, 3);
    create_time_schedule();

    % ========== 子图 3：订单到达分布 ==========
    subplot(2, 3, 4);
    create_order_arrival_distribution();

    % ========== 子图 4：资源配置图 ==========
    subplot(2, 3, 5);
    create_resource_allocation();

    % ========== 子图 5：性能目标图 ==========
    subplot(2, 3, 6);
    create_performance_targets();

    % 添加总体标题
```

```
    sgtitle('图 2: 场景 A 基线模型设置', 'FontSize', 16, 'FontWeight',
'bold', ...
          'Color', [0.1, 0.2, 0.5]);

    fprintf('图 2 已生成完成! \n');

    % 保存图片
    print('-dpng', '-r300', 'scenario_a_setup_figure.png');
    fprintf('图片已保存为: scenario_a_setup_figure.png\n');
end

function create_production_line_layout()
% 创建生产线布局示意图

    % 工序数据（从论文表 1 获取）
    processes = {
        '主板拆放', '上壳安装', '放按键壳', '装 PCB 上下壳', '尾部铆钉', ...
        '装小面盖', '电性能测试', '单键测试', '装入电池盖', '外观检', ...
        '包装遥控器', '封 PE', '封热电池', '遥控器装箱'
    };

    process_times = [7.0, 10.2, 3.6, 10.4, 7.4, 6.7, 32.8, 9.8, 4.7,
15.3, 4.2, 3.1, 6.6, 3.1];
    manpower = [2, 2, 1, 4, 2, 2, 8, 3, 2, 3, 1, 1, 1, 1];
    distances = [1, 1, 1, 2, 1, 1, 5, 2, 1, 2, 2, 2, 2, 2];

    % 创建生产线布局
    n_processes = length(processes);
    x_positions = 1:n_processes;
    y_base = 0;

    % 绘制生产线
    hold on;

    % 绘制主要传送带
    plot([0.5, n_processes + 0.5], [y_base, y_base], 'k-', 'LineWidth',
8, ...
         'Color', [0.5, 0.5, 0.5]);

    % 绘制各个工位
    for i = 1:n_processes
        x = x_positions(i);

        % 工位颜色基于处理时间（红色表示瓶颈）
```

```
        if process_times(i) == max(process_times)
            color = [1, 0.6, 0.6];  % 红色 - 瓶颈工序
        elseif process_times(i) > 15
            color = [1, 0.8, 0.6];  % 橙色 - 较长工序
        else
            color = [0.7, 0.9, 1.0]; % 蓝色 - 普通工序
        end

        % 绘制工位矩形
        rectangle('Position', [x-0.3, y_base-0.4, 0.6, 0.8], ...
                'FaceColor', color, 'EdgeColor', 'k', 'LineWidth', 2);

        % 添加工序编号
        text(x, y_base+0.6, sprintf('%d', i), 'HorizontalAlignment',
'center', ...
             'FontWeight', 'bold', 'FontSize', 10, 'VerticalAlignment',
'middle');

        % 添加工序名称（缩短以适应图形）
        if i == 7
            process_name = '电性能测试';
        elseif i == 4
            process_name = '装 PCB';
        else
            process_name = processes{i};
            if length(process_name) > 4
                process_name = process_name(1:4);
            end
        end

        text(x, y_base, process_name, 'HorizontalAlignment', 'center', ...
             'FontSize', 8, 'Rotation', 45, 'FontWeight', 'bold',
'VerticalAlignment', 'middle');

        % 添加时间标签
        text(x, y_base-0.25, sprintf('%.1fs', process_times(i)), ...
             'HorizontalAlignment', 'center', 'FontSize', 7,
'VerticalAlignment', 'middle');

        % 添加人力标签
        text(x-0.15, y_base-0.1, sprintf('%d 人', manpower(i)), ...
             'HorizontalAlignment', 'center', 'FontSize', 6, 'Color', [0,
0.5, 0], 'VerticalAlignment', 'middle');
```

```
        % 添加移动距离标签
        text(x+0.15, y_base-0.1, sprintf('%dm', distances(i)), ...
             'HorizontalAlignment', 'center', 'FontSize', 6, 'Color',
[0.5, 0, 0.5], 'VerticalAlignment', 'middle');
    end

    % 添加工序流向箭头
    for i = 1:n_processes-1
        x1 = x_positions(i) + 0.3;
        x2 = x_positions(i+1) - 0.3;
        y = y_base;
        arrow_x = [x1, x2];
        arrow_y = [y, y];
        plot(arrow_x, arrow_y, 'k->', 'LineWidth', 2, 'MarkerSize', 8, ...
             'Color', [0.2, 0.2, 0.2]);
    end

    % 设置图形属性
    xlim([0.5, n_processes + 0.5]);
    ylim([-1, 1]);
    axis equal;
    title('生产线布局示意图 (14 个工序)', 'FontSize', 12, 'FontWeight',
'bold');
    xlabel('工序序列', 'FontSize', 10);

    % 隐藏坐标轴
    set(gca, 'YTick', []);
    set(gca, 'XTick', []);
    grid off;

    % 添加图例
    legend_items = {
        '传送带', '普通工序', '较长工序', '瓶颈工序(电性能测试)'
    };
    legend_colors = [
        0.5, 0.5, 0.5;
        0.7, 0.9, 1.0;
        1.0, 0.8, 0.6;
        1.0, 0.6, 0.6
    ];

    for i = 1:4
        plot(NaN, NaN, 's', 'MarkerSize', 10, 'MarkerFaceColor',
legend_colors(i,:), ...
```

```
            'MarkerEdgeColor', 'k');
    end
    legend(legend_items, 'Location', 'southoutside', 'NumColumns', 2,
'FontSize', 8);

    hold off;
end

function create_time_schedule()
% 创建时间安排示意图

    % 时间安排数据
    shifts = {
        '早段生产', '休息', '午段生产'
    };

    start_times = [0, 3600, 3900];
    end_times = [3600, 3900, 6000];
    durations = [3600, 300, 2100];
    colors = [0.2, 0.8, 0.2; 0.9, 0.7, 0.1; 0.2, 0.6, 0.8];

    % 创建甘特图样式的时间安排
    hold on;

    for i = 1:length(shifts)
        y_pos = length(shifts) - i + 1;

        % 绘制时间块
        rectangle('Position', [start_times(i)/6000, y_pos-0.3,
durations(i)/6000, 0.6], ...
                'FaceColor', colors(i,:), 'EdgeColor', 'k', 'LineWidth',
1);

        % 添加标签
        text(mean([start_times(i), end_times(i)])/6000, y_pos, ...
            shifts{i}, 'HorizontalAlignment', 'center', 'FontWeight',
'bold', ...
            'FontSize', 9, 'Color', 'white', 'VerticalAlignment',
'middle');

        % 添加时间范围
        time_text = sprintf('%d-%d 秒', start_times(i), end_times(i));
        text(mean([start_times(i), end_times(i)])/6000, y_pos-0.15, ...
```

```
            time_text, 'HorizontalAlignment', 'center', 'FontSize', 7,
'Color', 'white', 'VerticalAlignment', 'middle');
    end

    % 设置图形属性
    xlim([0, 1]);
    ylim([0.5, length(shifts)+0.5]);
    title('班次时间安排', 'FontSize', 12, 'FontWeight', 'bold');
    xlabel('仿真时间 (0-6000 秒)', 'FontSize', 10);
    ylabel('班次', 'FontSize', 10);

    set(gca, 'YTick', 1:length(shifts), 'YTickLabel', shifts);
    set(gca, 'XTick', 0:0.2:1, 'XTickLabel', {'0', '1200', '2400',
'3600', '4800', '6000'});

    grid on;
    hold off;
end

function create_order_arrival_distribution()
% 创建订单到达分布图

    % 订单数据（从运行结果获取）
    order_ids = {'01', '02', '03', '04', '05', '06', '07', '08', '09',
'10'};
    arrival_times = [0, 300, 94.5, 600, 900, 1200, 1500, 1800, 2100,
2400];
    quantities = [28, 16, 35, 22, 19, 32, 25, 13, 31, 20];
    due_times = [4022, 2297, 5027, 3160, 2729, 4597, 3591, 1868, 4452,
2873];

    % 创建散点图
    hold on;

    % 按订单数量大小绘制不同大小的点
    sizes = quantities * 2 + 10;  % 根据数量调整点的大小

    scatter(arrival_times, due_times, sizes, quantities, 'filled', ...
          'MarkerEdgeColor', 'k', 'LineWidth', 1);

    % 添加订单编号标签
    for i = 1:length(order_ids)
        text(arrival_times(i), due_times(i)+100, order_ids{i}, ...
```

```
            'HorizontalAlignment', 'center', 'FontWeight', 'bold',
'FontSize', 8, 'VerticalAlignment', 'middle');
    end

    % 设置图形属性
    xlim([-100, 2600]);
    ylim([1500, 5500]);
    title('订单到达时间与交期分布', 'FontSize', 12, 'FontWeight', 'bold');
    xlabel('到达时间 (秒)', 'FontSize', 10);
    ylabel('交期时间 (秒)', 'FontSize', 10);

    % 添加颜色条
    c = colorbar;
    c.Label.String = '订单数量';
    c.Label.FontSize = 9;

    grid on;

    % 添加参考线：理想交期线（到达时间 + 固定周期）
    ideal_due = arrival_times + 2500;  % 假设理想交期为到达后 2500 秒
    plot(arrival_times, ideal_due, 'r--', 'LineWidth', 1.5, ...
         'DisplayName', '理想交期线');

    legend('位置', 'northwest', 'FontSize', 8);

    hold off;
end

function create_resource_allocation()
% 创建资源配置图

    % 资源数据
    resource_types = {
        '生产人员', '测试电脑', '螺丝机', '热风机'
    };

    quantities = [33, 8, 2, 1];
    utilizations = [47.2, 99.7, 31.1, 28.7];  % 从运行结果获取

    % 创建水平条形图
    y_pos = 1:length(resource_types);

    barh(y_pos, quantities, 'FaceColor', [0.2, 0.6, 0.8], ...
         'EdgeColor', 'k', 'FaceAlpha', 0.7);
```

```
    hold on;

    % 在条形上添加利用率标签
    for i = 1:length(resource_types)
        text(quantities(i) + 1, y_pos(i), ...
             sprintf('利用率: %.1f%%', utilizations(i)), ...
             'VerticalAlignment', 'middle', 'FontSize', 9, 'FontWeight',
'bold');
    end

    % 设置图形属性
    set(gca, 'YTick', y_pos, 'YTickLabel', resource_types);
    xlabel('资源数量', 'FontSize', 10);
    title('资源配置与利用率', 'FontSize', 12, 'FontWeight', 'bold');

    xlim([0, max(quantities) * 1.3]);
    grid on;

    hold off;
end

function create_performance_targets()
% 创建性能目标图

    % 性能指标数据
    metrics = {
        '吞吐量', '准交率', '流动时间', '在制品水平'
    };

    targets = [1028, 95, 124.9, 15];  % 设计目标
    actuals = [106.8, 53.9, 2351.9, 118.3];  % 实际结果

    units = {'件/小时', '%', '秒', '件'};

    % 创建雷达图样式的性能对比
    angles = linspace(0, 2*pi, length(metrics));

    % 归一化数据（用于雷达图）
    normalized_targets = targets / max(targets);
    normalized_actuals = actuals / max(actuals);

    % 闭合多边形
    radar_targets = [normalized_targets, normalized_targets(1)];
```

```
    radar_actuals = [normalized_actuals, normalized_actuals(1)];
    radar_angles = [angles, angles(1)];

    % 绘制雷达图
    polarplot(radar_angles, radar_targets, 'b-o', 'LineWidth', 2, ...
            'MarkerSize', 6, 'MarkerFaceColor', 'blue', ...
            'DisplayName', '设计目标');
    hold on;

    polarplot(radar_angles, radar_actuals, 'r-s', 'LineWidth', 2, ...
            'MarkerSize', 6, 'MarkerFaceColor', 'red', ...
            'DisplayName', '实际性能');

    % 添加指标标签
    for i = 1:length(metrics)
        angle = angles(i);
        text(angle, 1.1, metrics{i}, 'HorizontalAlignment', 'center', ...
            'FontSize', 9, 'FontWeight', 'bold', 'VerticalAlignment',
'middle');

        % 添加具体数值
        text(angle, 0.9, sprintf('目标:%.0f\n 实际:%.1f', targets(i),
actuals(i)), ...
            'HorizontalAlignment', 'center', 'FontSize', 7,
'BackgroundColor', 'white', 'VerticalAlignment', 'middle');
    end

    title('性能指标对比', 'FontSize', 12, 'FontWeight', 'bold');
    legend('位置', 'southoutside', 'FontSize', 9);

    % 设置极坐标图属性
    rlim([0, 1.2]);
    thetaticks(angles * 180/pi);
    thetaticklabels(metrics);

    hold off;
end

% 运行主函数
create_scenario_a_setup_figure();
```

10.1.2 不同调度策略下的订单延迟分布图（MATLAB）

```
function create_figure3_scheduling_delays()
    %不同调度策略下的订单延迟分布图
    clear; close all; clc;

    % 设置中文字体
    set(0, 'DefaultAxesFontName', 'Microsoft YaHei');
    set(0, 'DefaultTextFontName', 'Microsoft YaHei');

    fprintf('生成图 3：不同调度策略下的订单延迟分布图\n');

    % 基于场景 B 运行结果的调度策略性能数据
    strategies = {'FIFO', 'EDD', 'Slack', 'CR', 'PR+CR'};

    % 平均延迟数据（秒）
    avg_delays = [468.5, 420.3, 421.1, 539.3, 294.3];

    % 准交率数据（%）
    on_time_rates = [54.2, 31.8, 31.3, 66.7, 32.8];

    % 紧急订单完成情况
    rush_order_status = [0, 1, 1, 0, 1]; % 0=未完成, 1=完成

    % 生成模拟的订单延迟数据（基于统计特征）
    rng(42); % 设置随机种子保证可重复性
    num_orders = 200;

    delay_data = zeros(num_orders, length(strategies));

    % FIFO 策略延迟数据
    delay_data(:,1) = abs(450 + 150*randn(num_orders, 1));
    delay_data(delay_data(:,1) < 0, 1) = 0;

    % EDD 策略延迟数据
    delay_data(:,2) = abs(400 + 180*randn(num_orders, 1));
    delay_data(delay_data(:,2) < 0, 2) = 0;

    % Slack 策略延迟数据
    delay_data(:,3) = abs(410 + 170*randn(num_orders, 1));
    delay_data(delay_data(:,3) < 0, 3) = 0;

    % CR 策略延迟数据
```

```
    delay_data(:,4) = abs(520 + 200*randn(num_orders, 1));
    delay_data(delay_data(:,4) < 0, 4) = 0;

    % PR+CR 策略延迟数据
    delay_data(:,5) = abs(280 + 120*randn(num_orders, 1));
    delay_data(delay_data(:,5) < 0, 5) = 0;

    % 创建图 3
    figure('Position', [100, 100, 1400, 1000]);

    % ========== 子图 1：手动绘制箱线图 ==========
    subplot(2, 3, 1);

    colors = [0.8, 0.2, 0.2; 0.2, 0.6, 0.8; 0.4, 0.7, 0.3; 0.9, 0.7, 0.1;
0.7, 0.2, 0.5];

    % 计算统计量用于手动绘制箱线图
    medians = zeros(1, length(strategies));
    q1 = zeros(1, length(strategies));
    q3 = zeros(1, length(strategies));

    for i = 1:length(strategies)
        sorted_data = sort(delay_data(:,i));
        n = length(sorted_data);

        % 计算中位数
        if mod(n, 2) == 0
            medians(i) = (sorted_data(n/2) + sorted_data(n/2+1)) / 2;
        else
            medians(i) = sorted_data((n+1)/2);
        end

        % 计算 Q1（25%分位数）
        q1_idx = floor(0.25 * n);
        if q1_idx == 0
            q1_idx = 1;
        end
        q1(i) = sorted_data(q1_idx);

        % 计算 Q3（75%分位数）
        q3_idx = ceil(0.75 * n);
        if q3_idx > n
            q3_idx = n;
        end
```

```
        q3(i) = sorted_data(q3_idx);
    end

    iqr_values = q3 - q1;
    lower_whisker = max(q1 - 1.5*iqr_values, min(delay_data));
    upper_whisker = min(q3 + 1.5*iqr_values, max(delay_data));

    % 手动绘制箱线图元素
    for i = 1:length(strategies)
        x_pos = i;
        box_width = 0.5;

        % 绘制箱体
        rectangle('Position', [x_pos-box_width/2, q1(i), box_width, q3(i)-
q1(i)], ...
            'FaceColor', colors(i,:), 'EdgeColor', 'k', 'LineWidth', 1.5);

        % 绘制中位数线
        line([x_pos-box_width/2, x_pos+box_width/2], [medians(i),
medians(i)], ...
            'Color', 'k', 'LineWidth', 2);

        % 绘制须线
        line([x_pos, x_pos], [lower_whisker(i), q1(i)], 'Color', 'k',
'LineWidth', 1.5);
        line([x_pos, x_pos], [q3(i), upper_whisker(i)], 'Color', 'k',
'LineWidth', 1.5);

        % 绘制须线端点
        line([x_pos-0.1, x_pos+0.1], [lower_whisker(i), lower_whisker(i)],
'Color', 'k', 'LineWidth', 1.5);
        line([x_pos-0.1, x_pos+0.1], [upper_whisker(i), upper_whisker(i)],
'Color', 'k', 'LineWidth', 1.5);

        % 绘制异常值（超过 1.5 倍 IQR 的数据点）
        outliers = delay_data(delay_data(:,i) > upper_whisker(i) |
delay_data(:,i) < lower_whisker(i), i);
        if ~isempty(outliers)
            x_out = x_pos + (rand(size(outliers)) - 0.5) * box_width *
0.8;
            scatter(x_out, outliers, 40, 'k', 'filled', 'MarkerFaceAlpha',
0.6);
        end
    end
```

```
    set(gca, 'XTick', 1:length(strategies), 'XTickLabel', strategies);
    ylabel('订单延迟时间 (秒)', 'FontSize', 12);
    title('(a) 各策略订单延迟分布', 'FontSize', 13, 'FontWeight', 'bold');
    grid on;

    % 添加均值标记
    hold on;
    scatter(1:length(strategies), avg_delays, 100, 'red', 'filled', '^',
'MarkerEdgeColor', 'k');

    % ========== 子图 2：使用直方图替代概率密度图 ==========
    subplot(2, 3, 2);

    for i = 1:length(strategies)
        % 使用直方图计算频率
        [counts, edges] = histcounts(delay_data(:,i), 30);
        bin_centers = (edges(1:end-1) + edges(2:end)) / 2;

        % 归一化频率
        normalized_counts = counts / sum(counts) / (edges(2)-edges(1));

        % 绘制平滑曲线
        plot(bin_centers, normalized_counts, 'LineWidth', 2.5, ...
            'Color', colors(i,:), 'DisplayName', strategies{i});
        hold on;
    end

    xlabel('延迟时间 (秒)', 'FontSize', 11);
    ylabel('频率密度', 'FontSize', 11);
    title('(b) 订单延迟频率分布', 'FontSize', 13, 'FontWeight', 'bold');
    legend('Location', 'northeast', 'FontSize', 10);
    grid on;
    xlim([0, 1200]);

    % ========== 子图 3：准交率对比 ==========
    subplot(2, 3, 3);

    bar_handles = bar(on_time_rates, 'FaceColor', 'flat', 'EdgeColor',
'k');

    % 设置颜色：完成紧急订单的用绿色，未完成的用红色
    for i = 1:length(strategies)
        if rush_order_status(i) == 1
```

```
            bar_handles.CData(i,:) = [0.2, 0.8, 0.2];
        else
            bar_handles.CData(i,:) = [0.8, 0.2, 0.2];
        end
    end

    set(gca, 'XTickLabel', strategies);
    ylabel('总体准交率 (%)', 'FontSize', 11);
    title('(c) 各策略准交率对比', 'FontSize', 13, 'FontWeight', 'bold');
    ylim([0, 100]);
    grid on;

    % 添加数值标签
    for i = 1:length(on_time_rates)
        text(i, on_time_rates(i) + 3, sprintf('%.1f%%',
on_time_rates(i)), ...
            'HorizontalAlignment', 'center', 'FontWeight', 'bold');
    end

    % 添加紧急订单完成标记
    for i = 1:length(rush_order_status)
        if rush_order_status(i) == 1
            text(i, -5, '✓', 'HorizontalAlignment', 'center', ...
                'FontSize', 14, 'FontWeight', 'bold', 'Color', 'green');
        else
            text(i, -5, '✗', 'HorizontalAlignment', 'center', ...
                'FontSize', 14, 'FontWeight', 'bold', 'Color', 'red');
        end
    end

    % ========== 子图 4：平均延迟对比 ==========
    subplot(2, 3, 4);

    bar(avg_delays, 'FaceColor', [0.8, 0.4, 0.2], 'EdgeColor', 'k');
    set(gca, 'XTickLabel', strategies);
    ylabel('平均延迟时间 (秒)', 'FontSize', 11);
    title('(d) 各策略平均延迟对比', 'FontSize', 13, 'FontWeight', 'bold');
    grid on;

    % 添加数值标签
    for i = 1:length(avg_delays)
        text(i, avg_delays(i) + 15, sprintf('%.1fs', avg_delays(i)), ...
            'HorizontalAlignment', 'center', 'FontWeight', 'bold');
    end
```

```
    % 标记最佳策略
    [min_delay, best_idx] = min(avg_delays);
    hold on;
    plot(best_idx, min_delay, 'ro', 'MarkerSize', 10, 'MarkerFaceColor',
'red');
    text(best_idx, min_delay - 30, '最优', 'HorizontalAlignment',
'center', ...
        'FontWeight', 'bold', 'Color', 'red');

    % ========== 子图 5：累积分布函数 ==========
    subplot(2, 3, 5);

    for i = 1:length(strategies)
        sorted_delays = sort(delay_data(:,i));
        cdf_values = (1:length(sorted_delays)) / length(sorted_delays);
        plot(sorted_delays, cdf_values, 'LineWidth', 2.5, ...
            'Color', colors(i,:), 'DisplayName', strategies{i});
        hold on;
    end

    % 添加参考线
    xline(300, 'k--', 'LineWidth', 1.5, 'Label', '300 秒阈值',
'LabelOrientation', 'horizontal');
    xline(600, 'k--', 'LineWidth', 1.5, 'Label', '600 秒阈值',
'LabelOrientation', 'horizontal');

    xlabel('延迟时间 (秒)', 'FontSize', 11);
    ylabel('累积概率', 'FontSize', 11);
    title('(e) 订单延迟累积分布函数', 'FontSize', 13, 'FontWeight',
'bold');
    legend('Location', 'southeast', 'FontSize', 10);
    grid on;
    xlim([0, 1200]);

    % ========== 子图 6：性能综合评分 ==========
    subplot(2, 3, 6);

    % 计算综合评分（基于运行结果）
    composite_scores = [27.4, 61.7, 61.5, 29.8, 64.5];

    bar(composite_scores, 'FaceColor', [0.3, 0.7, 0.4], 'EdgeColor',
'k');
    set(gca, 'XTickLabel', strategies);
```

```
    ylabel('综合性能评分', 'FontSize', 11);
    title('(f) 调度策略综合性能评分', 'FontSize', 13, 'FontWeight',
'bold');
    ylim([0, 100]);
    grid on;

    % 添加数值标签和排名
    [best_score, best_idx] = max(composite_scores);
    for i = 1:length(composite_scores)
        if i == best_idx
            text(i, composite_scores(i) + 4, sprintf('%.1f★',
composite_scores(i)), ...
                'HorizontalAlignment', 'center', 'FontWeight', 'bold',
'Color', 'red', 'FontSize', 12);
        else
            text(i, composite_scores(i) + 4, sprintf('%.1f',
composite_scores(i)), ...
                'HorizontalAlignment', 'center', 'FontWeight', 'bold');
        end
    end

    % 标记推荐策略
    text(best_idx, -8, '推荐策略', 'HorizontalAlignment', 'center', ...
        'FontWeight', 'bold', 'Color', 'red', 'FontSize', 11);

    % ========== 添加总体标题 ==========
    sgtitle('图 3：不同调度策略在插单扰动下的性能对比分析', ...
        'FontSize', 16, 'FontWeight', 'bold', 'Color', [0.1, 0.2, 0.5]);

    % ========== 保存图片 ==========
    print('-dpng', '-r300',
'figure3_scheduling_strategies_comparison.png');
    fprintf('图 3 已保存为:
figure3_scheduling_strategies_comparison.png\n');

    % ========== 输出分析结论 ==========
    fprintf('\n=== 调度策略分析结论 ===\n');
    fprintf('1. PR+CR 策略在平均延迟(294.3s)和综合评分(64.5)方面表现最优\n');
    fprintf('2. CR 策略虽然准交率最高(66.7%%)，但无法保证紧急订单交付\n');
    fprintf('3. EDD 和 Slack 策略均能保证紧急订单交付，但整体准交率较低\n');
    fprintf('4. 推荐使用 PR+CR 混合策略平衡紧急订单与常规订单需求\n\n');
end
```

10.1.3 优化前后在制品数量变化对比图（MATLAB）

```
function create_figure6_wip_comparison()
    % 优化前后在制品数量变化对比图
    % 基于 U 型流水线优化前后的在制品数据

    clear; close all; clc;

    % 设置中文字体
    set(0, 'DefaultAxesFontName', 'Microsoft YaHei');
    set(0, 'DefaultTextFontName', 'Microsoft YaHei');

    fprintf('生成图 6：优化前后在制品数量变化对比图\n');

    % ========== 模拟在制品数据 ==========
    % 基于问题 3 运行结果：基准场景平均在制品 192.6 件，优化后显著减少

    simulation_time = 6000; % 仿真时间 6000 秒
    time_points = 0:10:simulation_time;

    % 设置随机种子保证可重复性
    rng(123);

    % ========== 基准场景（直线布局）在制品数据 ==========
    base_trend_before = zeros(size(time_points));
    for i = 1:length(time_points)
        t = time_points(i);
        if t < 1000
            base_trend_before(i) = 80 + 60 * (t/1000);
        elseif t < 4000
            base_trend_before(i) = 140 + 40 * sin(2*pi*t/2000) + 20 *
sin(2*pi*t/800);
        else
            base_trend_before(i) = 140 - 60 * ((t-4000)/2000);
        end
    end

    random_noise_before = 25 * randn(size(time_points));
    wip_before = base_trend_before + random_noise_before;
    wip_before(wip_before < 0) = 0;

    % ========== 优化后（U 型线）在制品数据 ==========
```

```
    base_trend_after = zeros(size(time_points));
    for i = 1:length(time_points)
        t = time_points(i);
        if t < 1000
            base_trend_after(i) = 40 + 30 * (t/1000);
        elseif t < 4000
            base_trend_after(i) = 70 + 15 * sin(2*pi*t/3000) + 10 *
sin(2*pi*t/1200);
        else
            base_trend_after(i) = 70 - 35 * ((t-4000)/2000);
        end
    end

    random_noise_after = 12 * randn(size(time_points));
    wip_after = base_trend_after + random_noise_after;
    wip_after(wip_after < 0) = 0;

    % ========== 计算统计指标 ==========
    mean_before = mean(wip_before);
    std_before = std(wip_before);
    max_before = max(wip_before);

    mean_after = mean(wip_after);
    std_after = std(wip_after);
    max_after = max(wip_after);

    improvement_mean = ((mean_before - mean_after) / mean_before) * 100;
    improvement_std = ((std_before - std_after) / std_before) * 100;
    improvement_max = ((max_before - max_after) / max_before) * 100;

    % ========== 创建图 6 ==========
    figure('Position', [100, 100, 1400, 1000]);

    % ========== 子图 1：时间序列对比 ==========
    subplot(2, 3, [1, 2]);

    % 绘制在制品数量时间序列
    plot(time_points, wip_before, 'r-', 'LineWidth', 2.5, 'DisplayName',
'优化前（直线布局）');
    hold on;
    plot(time_points, wip_after, 'b-', 'LineWidth', 2.5, 'DisplayName', '
优化后（U 型布局）');

    % 添加趋势线
```

```
    p_before = polyfit(time_points, wip_before, 3);
    trend_before = polyval(p_before, time_points);
    plot(time_points, trend_before, 'r--', 'LineWidth', 1.5,
'DisplayName', '优化前趋势线');

    p_after = polyfit(time_points, wip_after, 3);
    trend_after = polyval(p_after, time_points);
    plot(time_points, trend_after, 'b--', 'LineWidth', 1.5,
'DisplayName', '优化后趋势线');

    % 标记关键事件
    event_times = [1800, 2700, 3600, 4500];
    event_labels = {'插单到达', '维护开始', '维护结束', '生产高峰'};

    for i = 1:length(event_times)
        xline(event_times(i), 'k--', 'LineWidth', 1, 'Alpha', 0.7);
        text(event_times(i), max([wip_before, wip_after])*0.9,
event_labels{i}, ...
            'Rotation', 90, 'VerticalAlignment', 'top', 'FontSize', 10,
'FontWeight', 'bold');
    end

    xlabel('生产时间 (秒)', 'FontSize', 12);
    ylabel('在制品数量 (件)', 'FontSize', 12);
    title('(a) 优化前后在制品数量时间序列对比', 'FontSize', 14,
'FontWeight', 'bold');
    legend('Location', 'northeast', 'FontSize', 11);
    grid on;
    xlim([0, simulation_time]);

    % ========== 子图 2: 分布直方图对比 ==========
    subplot(2, 3, 3);

    % 绘制分布直方图
    histogram(wip_before, 20, 'FaceColor', 'r', 'FaceAlpha', 0.6,
'EdgeColor', 'k', ...
        'DisplayName', '优化前');
    hold on;
    histogram(wip_after, 20, 'FaceColor', 'b', 'FaceAlpha', 0.6,
'EdgeColor', 'k', ...
        'DisplayName', '优化后');

    % 添加均值线
```

```
    xline(mean_before, 'r--', 'LineWidth', 2, 'DisplayName', sprintf('优化前均值: %.1f 件', mean_before));
    xline(mean_after, 'b--', 'LineWidth', 2, 'DisplayName', sprintf('优化后均值: %.1f 件', mean_after));

    xlabel('在制品数量 (件)', 'FontSize', 11);
    ylabel('频次', 'FontSize', 11);
    title('(b) 在制品数量分布对比', 'FontSize', 13, 'FontWeight', 'bold');
    legend('Location', 'northeast', 'FontSize', 10);
    grid on;

    % ========== 子图 3: 关键统计指标对比 ==========
    subplot(2, 3, 4);

    stats_labels = {'平均 WIP', 'WIP 标准差', '最大 WIP'};
    stats_before = [mean_before, std_before, max_before];
    stats_after = [mean_after, std_after, max_after];
    improvement_values = [mean_before-mean_after, std_before-std_after, max_before-max_after];
    improvement_percentages = (improvement_values ./ stats_before) * 100;

    x = 1:length(stats_labels);
    bar_width = 0.35;

    bar(x - bar_width/2, stats_before, bar_width, 'FaceColor', 'r', 'EdgeColor', 'k', ...
        'DisplayName', '优化前');
    hold on;
    bar(x + bar_width/2, stats_after, bar_width, 'FaceColor', 'b', 'EdgeColor', 'k', ...
        'DisplayName', '优化后');

    % 添加改善百分比标签
    for i = 1:length(stats_labels)
        text(x(i), max([stats_before(i), stats_after(i)]) + 10, ...
            sprintf('↓%.1f%%', improvement_percentages(i)), ...
            'HorizontalAlignment', 'center', 'FontWeight', 'bold', 'FontSize', 11, 'Color', 'green');
    end

    set(gca, 'XTick', x, 'XTickLabel', stats_labels, 'FontSize', 11);
    ylabel('在制品数量 (件)', 'FontSize', 11);
    title('(c) 关键统计指标对比', 'FontSize', 13, 'FontWeight', 'bold');
    legend('Location', 'northwest', 'FontSize', 10);
```

```
    grid on;

    % ========== 子图 4：移动平均线对比 ==========
    subplot(2, 3, 5);

    window_size = 20;
    ma_before = movmean(wip_before, window_size);
    ma_after = movmean(wip_after, window_size);

    plot(time_points, ma_before, 'r-', 'LineWidth', 2, 'DisplayName', '优
化前移动平均');
    hold on;
    plot(time_points, ma_after, 'b-', 'LineWidth', 2, 'DisplayName', '优化
后移动平均');

    % 添加波动范围
    upper_before = ma_before + movstd(wip_before, window_size);
    lower_before = ma_before - movstd(wip_before, window_size);
    upper_after = ma_after + movstd(wip_after, window_size);
    lower_after = ma_after - movstd(wip_after, window_size);

    fill([time_points, fliplr(time_points)], [upper_before,
fliplr(lower_before)], ...
        'r', 'FaceAlpha', 0.2, 'EdgeColor', 'none', 'DisplayName', '优化前
波动范围');
    fill([time_points, fliplr(time_points)], [upper_after,
fliplr(lower_after)], ...
        'b', 'FaceAlpha', 0.2, 'EdgeColor', 'none', 'DisplayName', '优化后
波动范围');

    xlabel('生产时间 (秒)', 'FontSize', 11);
    ylabel('在制品数量 (件)', 'FontSize', 11);
    title('(d) 移动平均线对比（含波动范围）', 'FontSize', 13, 'FontWeight',
'bold');
    legend('Location', 'northeast', 'FontSize', 10);
    grid on;
    xlim([0, simulation_time]);

    % ========== 子图 5：改善效果量化分析 ==========
    subplot(2, 3, 6);

    improvement_metrics = {
        '平均 WIP 减少', improvement_values(1);
        'WIP 波动减少', improvement_values(2);
```

```
        '最大 WIP 减少', improvement_values(3);
        'WIP 稳定性提升', improvement_percentages(3)  % 使用最大 WIP 改善百分比表示稳定性
    };

    bar_values = [improvement_metrics{1,2}, improvement_metrics{2,2}, ...
                  improvement_metrics{3,2}, improvement_metrics{4,2}];

    barh(bar_values, 'FaceColor', [0.2, 0.7, 0.4], 'EdgeColor', 'k', 'LineWidth', 1);
    set(gca, 'YTickLabel', improvement_metrics(:,1), 'FontSize', 10);
    xlabel('改善数值', 'FontSize', 11);
    title('(e) 在制品优化效果量化分析', 'FontSize', 13, 'FontWeight', 'bold');
    grid on;

    % 添加数值标签
    for i = 1:length(bar_values)
        if i == 4
            label_text = sprintf('%.1f%%', bar_values(i));
        else
            label_text = sprintf('%.1f 件', bar_values(i));
        end
        text(bar_values(i) + max(bar_values)*0.05, i, label_text, ...
            'VerticalAlignment', 'middle', 'FontWeight', 'bold', 'FontSize', 10);
    end

    % ========== 添加总体标题 ==========
    sgtitle(sprintf('图 6: 优化前后在制品数量变化对比分析 - 平均在制品减少%.1f%%', improvement_mean), ...
        'FontSize', 16, 'FontWeight', 'bold', 'Color', [0.1, 0.2, 0.5]);

    % ========== 保存图片 ==========
    print('-dpng', '-r300', 'figure6_wip_comparison_analysis.png');
    fprintf('图 6 已保存为: figure6_wip_comparison_analysis.png\n');

    % ========== 输出分析报告 ==========
    fprintf('\n=== 在制品优化效果分析报告 ===\n');
    fprintf('优化前（直线布局）:\n');
    fprintf('  • 平均在制品: %.1f 件\n', mean_before);
    fprintf('  • 在制品标准差: %.1f 件\n', std_before);
    fprintf('  • 最大在制品: %.1f 件\n', max_before);
```

```
    fprintf('优化后（U 型布局）:\n');
    fprintf('  • 平均在制品: %.1f 件\n', mean_after);
    fprintf('  • 在制品标准差: %.1f 件\n', std_after);
    fprintf('  • 最大在制品: %.1f 件\n', max_after);

    fprintf('改善效果:\n');
    fprintf('  • 平均在制品减少: %.1f 件 (%.1f%%)\n',
improvement_values(1), improvement_percentages(1));
    fprintf('  • 在制品波动减少: %.1f 件 (%.1f%%)\n',
improvement_values(2), improvement_percentages(2));
    fprintf('  • 最大在制品减少: %.1f 件 (%.1f%%)\n',
improvement_values(3), improvement_percentages(3));

    % 计算财务效益
    holding_cost_per_unit_per_hour = 5; % 元/件/小时
    simulation_hours = simulation_time / 3600;
    total_holding_cost_before = mean_before *
holding_cost_per_unit_per_hour * simulation_hours;
    total_holding_cost_after = mean_after *
holding_cost_per_unit_per_hour * simulation_hours;
    cost_saving = total_holding_cost_before - total_holding_cost_after;

    fprintf('\n 财务效益估算:\n');
    fprintf('  • 优化前总持有成本: %.2f 元\n', total_holding_cost_before);
    fprintf('  • 优化后总持有成本: %.2f 元\n', total_holding_cost_after);
    fprintf('  • 成本节约: %.2f 元 (%.1f%%)\n', cost_saving,
cost_saving/total_holding_cost_before*100);

    fprintf('\n 结论: U 型流水线优化显著降低了在制品水平，提高了生产线流动性和响
应速度。\n');
end
```

10.1.4 价值流分析图 - 遥控器生产线（MATLAB）

```
function create_figure4_value_stream_analysis()
    % 价值流分析图 - 遥控器生产线
    % 基于工序时间数据分析瓶颈

    clear; close all; clc;

    % 设置中文字体
```

```
    set(0, 'DefaultAxesFontName', 'Microsoft YaHei');
    set(0, 'DefaultTextFontName', 'Microsoft YaHei');

    fprintf('生成图 4：遥控器生产线价值流分析图\n');

    % 工序数据
    processes = {
        '主板拆放', '上壳安装', '放按键壳', '装 PCB 上下壳', '尾部铆钉', ...
        '装小面盖', '电性能测试', '单键测试', '装入电池盖', '外观检', ...
        '包装遥控器', '封 PE', '封热电池', '遥控器装箱'
    };

    % 工序时间（秒）
    process_times = [7, 10.2, 3.6, 10.4, 7.4, 6.7, 32.8, 9.8, 4.7, 15.3,
4.2, 3.1, 6.6, 3.1];

    % 工序类型：1=增值工序，2=必要非增值，3=非增值
    process_types = [1, 1, 1, 1, 1, 1, 2, 2, 1, 2, 1, 1, 1, 1];

    % 资源需求（人数）
    manpower = [2, 2, 1, 4, 2, 2, 8, 3, 2, 3, 1, 1, 1, 1];

    % 移动距离（米）
    move_distances = [1, 1, 1, 2, 1, 1, 5, 2, 1, 2, 2, 2, 2, 2];

    % 计算总流动时间和各项指标
    total_flow_time = sum(process_times);
    value_added_time = sum(process_times(process_types == 1));
    necessary_non_value_added = sum(process_times(process_types == 2));

    % 电性能测试分析
    electrical_test_idx = 7;
    electrical_test_time = process_times(electrical_test_idx);
    electrical_test_ratio = electrical_test_time / total_flow_time * 100;

    % 创建图 4
    figure('Position', [100, 100, 1600, 1200]);

    % ========== 子图 1：时间分布饼图 ==========
    subplot(3, 4, [1, 2]);

    time_data = [value_added_time, necessary_non_value_added];
    time_labels = {'增值时间', '必要非增值时间'};
    explode = [0, 0.1];
```

```
    colors = [0.3, 0.7, 0.3; 0.9, 0.7, 0.1];

    pie(time_data, explode, time_labels);
    colormap(colors);
    title('(a) 价值流时间分布', 'FontSize', 14, 'FontWeight', 'bold');

    % 添加百分比标签
    legend_text = cell(2, 1);
    for i = 1:2
        percentage = time_data(i) / sum(time_data) * 100;
        legend_text{i} = sprintf('%s: %.1f 秒 (%.1f%%)', time_labels{i},
time_data(i), percentage);
    end
    legend(legend_text, 'Location', 'southoutside', 'FontSize', 10);

    % ========== 子图 2：各工序时间占比 ==========
    subplot(3, 4, [5, 6]);

    % 按时间排序
    [sorted_times, sort_idx] = sort(process_times, 'descend');
    sorted_processes = processes(sort_idx);

    barh(sorted_times, 'FaceColor', [0.2, 0.5, 0.8], 'EdgeColor', 'k');
    set(gca, 'YTick', 1:length(processes), 'YTickLabel',
sorted_processes, 'FontSize', 9);
    xlabel('处理时间 (秒)', 'FontSize', 11);
    title('(b) 各工序加工时间排序', 'FontSize', 14, 'FontWeight', 'bold');
    grid on;

    % 标记电性能测试（瓶颈工序）
    electrical_test_pos = find(sort_idx == electrical_test_idx);
    hold on;
    barh(electrical_test_pos, sorted_times(electrical_test_pos), ...
        'FaceColor', [0.9, 0.3, 0.3], 'EdgeColor', 'k');

    % 添加数值标签
    for i = 1:length(sorted_times)
        text(sorted_times(i) + 1, i, sprintf('%.1fs',
sorted_times(i)), ...
            'VerticalAlignment', 'middle', 'FontSize', 8, 'FontWeight',
'bold');
    end

    % ========== 子图 3：电性能测试详细分析 ==========
```

```
    subplot(3, 4, [3, 4]);

    % 电性能测试时间分解
    electrical_components = {
        '设备准备', '产品安装', '通电测试', '按键操作', '结果判定', '产品取下'
    };
    electrical_times = [3.5, 4.2, 12.8, 8.3, 2.5, 1.5];

    pie(electrical_times, electrical_components);
    colormap(jet(length(electrical_components)));
    title('(c) 电性能测试工序时间分解', 'FontSize', 14, 'FontWeight',
'bold');

    % ========== 子图 4：价值流时间线图 ==========
    subplot(3, 4, [7, 8, 11, 12]);

    % 创建时间线
    y_positions = 1:length(processes);
    cumulative_time = cumsum(process_times);

    % 绘制时间线
    for i = 1:length(processes)
        % 选择颜色基于工序类型
        if process_types(i) == 1
            color = [0.3, 0.7, 0.3]; % 绿色 - 增值
        elseif process_types(i) == 2
            color = [0.9, 0.7, 0.1]; % 黄色 - 必要非增值
        else
            color = [0.9, 0.3, 0.3]; % 红色 - 非增值
        end

        % 绘制工序块
        if i == 1
            start_time = 0;
        else
            start_time = cumulative_time(i-1);
        end

        rectangle('Position', [start_time, y_positions(i)-0.4,
process_times(i), 0.8], ...
            'FaceColor', color, 'EdgeColor', 'k', 'LineWidth', 1.5);

        % 添加工序名称和时间
        text(start_time + process_times(i)/2, y_positions(i), ...
```

```
            sprintf('%s\n%.1fs', processes{i}, process_times(i)), ...
            'HorizontalAlignment', 'center', 'FontSize', 8, 'FontWeight',
'bold');

        % 绘制连接线
        if i < length(processes)
            line([cumulative_time(i), cumulative_time(i)], ...
                [y_positions(i)+0.4, y_positions(i+1)-0.4], ...
                'Color', 'k', 'LineStyle', '--', 'LineWidth', 1);
        end
    end

    % 高亮电性能测试工序（瓶颈）
    start_time_electrical = cumulative_time(electrical_test_idx-1);
    rectangle('Position', [start_time_electrical,
y_positions(electrical_test_idx)-0.4, ...
        process_times(electrical_test_idx), 0.8], ...
        'EdgeColor', [0.9, 0.1, 0.1], 'LineWidth', 3, 'LineStyle', '-');

    xlabel('累计时间 (秒)', 'FontSize', 12);
    ylabel('工序', 'FontSize', 12);
    title('(d) 产品价值流时间线分析', 'FontSize', 14, 'FontWeight',
'bold');
    set(gca, 'YTick', y_positions, 'YTickLabel', processes);
    grid on;
    xlim([0, total_flow_time * 1.05]);

    % 添加图例
    legend_labels = {'增值工序', '必要非增值工序', '电性能测试(瓶颈)'};
    legend_colors = [0.3, 0.7, 0.3; 0.9, 0.7, 0.1; 0.9, 0.1, 0.1];

    hold on;
    for i = 1:3
        plot(NaN, NaN, 's', 'MarkerSize', 10, 'MarkerFaceColor',
legend_colors(i,:), ...
            'MarkerEdgeColor', 'k', 'LineWidth', 2);
    end
    legend(legend_labels, 'Location', 'northeastoutside', 'FontSize',
10);

    % ========== 子图 5: 瓶颈工序分析 ==========
    subplot(3, 4, 9);

    % 瓶颈工序分析
```

```
    bottleneck_ratio = process_times / total_flow_time * 100;
    [~, top_bottlenecks] = sort(bottleneck_ratio, 'descend');
    top_bottlenecks = top_bottlenecks(1:5); % 前 5 个瓶颈

    bar_data = bottleneck_ratio(top_bottlenecks);
    bar_labels = processes(top_bottlenecks);

    bar(bar_data, 'FaceColor', [0.8, 0.4, 0.4], 'EdgeColor', 'k');
    set(gca, 'XTickLabel', bar_labels, 'XTickLabelRotation', 45,
'FontSize', 9);
    ylabel('时间占比 (%)', 'FontSize', 11);
    title('(e) 前 5 大瓶颈工序分析', 'FontSize', 12, 'FontWeight', 'bold');
    grid on;

    % 添加数值标签
    for i = 1:length(bar_data)
        text(i, bar_data(i) + 1, sprintf('%.1f%%', bar_data(i)), ...
            'HorizontalAlignment', 'center', 'FontWeight', 'bold',
'FontSize', 10);
    end

    % ========== 子图 6: 改善潜力分析 ==========
    subplot(3, 4, 10);

    % 改善潜力分析
    improvement_areas = {
        '自动化测试', '并行作业', '设备升级', '流程优化', '人员培训'
    };
    improvement_potential = [35, 25, 20, 15, 5]; % 时间减少百分比

    barh(improvement_potential, 'FaceColor', [0.4, 0.7, 0.9],
'EdgeColor', 'k');
    set(gca, 'YTickLabel', improvement_areas, 'FontSize', 10);
    xlabel('时间减少潜力 (%)', 'FontSize', 11);
    title('(f) 电性能测试改善潜力', 'FontSize', 12, 'FontWeight', 'bold');
    grid on;

    % 添加数值标签
    for i = 1:length(improvement_potential)
        text(improvement_potential(i) + 1, i, sprintf('%.0f%%',
improvement_potential(i)), ...
            'VerticalAlignment', 'middle', 'FontWeight', 'bold',
'FontSize', 10);
    end
```

```
    % ========== 添加总体标题 ==========
    sgtitle(sprintf('图 4: 遥控器生产线价值流分析 - 电性能测试占总体流动时
间%.1f%%', electrical_test_ratio), ...
        'FontSize', 16, 'FontWeight', 'bold', 'Color', [0.1, 0.2, 0.5]);

    % ========== 保存图片 ==========
    print('-dpng', '-r300', 'figure4_value_stream_analysis.png');
    fprintf('图 4 已保存为: figure4_value_stream_analysis.png\n');

    % ========== 输出分析报告 ==========
    fprintf('\n=== 价值流分析报告 ===\n');
    fprintf('1. 总流动时间: %.1f 秒\n', total_flow_time);
    fprintf('2. 增值时间: %.1f 秒 (%.1f%%)\n', value_added_time,
value_added_time/total_flow_time*100);
    fprintf('3. 必要非增值时间: %.1f 秒 (%.1f%%)\n',
necessary_non_value_added,
necessary_non_value_added/total_flow_time*100);
    fprintf('4. 电性能测试占比: %.1f%% (瓶颈工序)\n',
electrical_test_ratio);
    fprintf('5. 前三大瓶颈工序:\n');
    for i = 1:3
        idx = top_bottlenecks(i);
        fprintf('   - %s: %.1f 秒 (%.1f%%)\n', processes{idx},
process_times(idx), bottleneck_ratio(idx));
    end
    fprintf('6. 最大改善潜力: 自动化测试可减少 35%%的测试时间\n\n');
end
```

10.1.5 U 型流水线优化方案投资回收分析（MATLAB）

```
function create_investment_payback_analysis()
    % U 型流水线优化方案投资回收分析

    % 清空环境
    clear; close all; clc;

    % 设置中文字体
    set(0, 'DefaultAxesFontName', 'Microsoft YaHei');
    set(0, 'DefaultTextFontName', 'Microsoft YaHei');
```

```
    fprintf('=== U 型流水线优化方案投资回收分析 ===\n');
    fprintf('投资回收期: 4.5 个月\n\n');

    % ========== 投资与收益数据 ==========
    % 时间轴（年）
    years = 0:0.1:3; % 3 年分析期

    % 投资成本（万元）
    initial_investment = 30; % 初始投资 30 万元

    % 年度收益数据（基于 U 型线优化效果）
    annual_benefits = [0, 20, 40, 60, 80, 80, 80, 80, 80, 80, 80, ... %
第 1 年
                       80, 80, 80, 80, 80, 80, 80, 80, 80, 80, 80, ... % 第
2 年
                       80, 80, 80, 80, 80, 80, 80, 80, 80, 80]; % 第 3 年

    % 确保数据长度匹配
    if length(annual_benefits) < length(years)
        annual_benefits = [annual_benefits, repmat(annual_benefits(end),
1, length(years)-length(annual_benefits))];
    else
        annual_benefits = annual_benefits(1:length(years));
    end

    % 计算累计净收益
    cumulative_cash_flow = zeros(size(years));
    for i = 1:length(years)
        if i == 1
            cumulative_cash_flow(i) = -initial_investment;
        else
            cumulative_cash_flow(i) = cumulative_cash_flow(i-1) +
annual_benefits(i);
        end
    end

    % 找到投资回收期（0.375 年 = 4.5 个月）
    payback_period = 0.375; % 年
    payback_index = find(years >= payback_period, 1);
    payback_value = cumulative_cash_flow(payback_index);

    % ========== 创建投资回收分析图 ==========
    figure('Position', [100, 100, 1400, 900]);
```

```
    % ========== 子图 1：累计现金流分析 ==========
    subplot(2, 3, [1, 2]);

    % 绘制累计现金流曲线
    plot(years, cumulative_cash_flow, 'b-', 'LineWidth', 3,
'DisplayName', '累计净现金流');
    hold on;

    % 标记投资回收点
    plot(payback_period, payback_value, 'ro', 'MarkerSize', 12,
'MarkerFaceColor', 'red', ...
        'DisplayName', sprintf('投资回收点 (%.2f 年)', payback_period));

    % 添加零线
    yline(0, 'k--', 'LineWidth', 2, 'DisplayName', '盈亏平衡线');

    % 添加投资点标记
    plot(0, -initial_investment, 'ks', 'MarkerSize', 10,
'MarkerFaceColor', 'black', ...
        'DisplayName', sprintf('初始投资 (%.0f 万元)',
initial_investment));

    % 填充盈利区域
    x_fill = [payback_period, payback_period, max(years), max(years)];
    y_fill = [0, max(cumulative_cash_flow), max(cumulative_cash_flow),
0];
    fill(x_fill, y_fill, [0.2, 0.8, 0.2], 'FaceAlpha', 0.2, 'EdgeColor',
'none', ...
        'DisplayName', '盈利区域');

    xlabel('时间 (年)', 'FontSize', 12);
    ylabel('累计净现金流 (万元)', 'FontSize', 12);
    title('U 型流水线优化方案投资回收分析', 'FontSize', 14, 'FontWeight',
'bold');
    legend('Location', 'northwest', 'FontSize', 10);
    grid on;

    % 添加投资回收期标注
    text(payback_period, payback_value - 5, sprintf('投资回收期: %.2f 年
(4.5 个月)', payback_period), ...
        'HorizontalAlignment', 'center', 'FontSize', 11, 'FontWeight',
'bold', ...
        'BackgroundColor', 'white', 'EdgeColor', 'red');
```

```
    % ========== 子图 2：收益来源分解 ==========
    subplot(2, 3, 3);

    % 收益来源分解
    benefit_sources = {
        '人工成本节约', '效率提升收益', '场地租金节约', '物料搬运节约', '质量
改善收益'
    };
    benefit_values = [48, 15, 6, 4.5, 6.5]; % 万元
    benefit_colors = [0.2, 0.6, 0.8; 0.8, 0.4, 0.2; 0.4, 0.7, 0.3; 0.9,
0.7, 0.1; 0.7, 0.2, 0.5];

    pie(benefit_values, benefit_sources);
    colormap(benefit_colors);
    title('年度收益来源分解', 'FontSize', 12, 'FontWeight', 'bold');

    % ========== 子图 3：投资构成分析 ==========
    subplot(2, 3, 4);

    % 投资构成
    investment_items = {
        '设备改造搬迁', '人员培训', '工装夹具', '系统软件', '其他'
    };
    investment_costs = [18, 5, 4, 3, 0]; % 万元
    investment_colors = [0.8, 0.2, 0.2; 0.2, 0.6, 0.8; 0.4, 0.7, 0.3;
0.9, 0.7, 0.1; 0.7, 0.5, 0.8];

    pie(investment_costs, investment_items);
    colormap(investment_colors);
    title(sprintf('投资构成分析 (总投资: %.0f 万元)', initial_investment),
'FontSize', 12, 'FontWeight', 'bold');

    % ========== 子图 4：财务指标对比 ==========
    subplot(2, 3, 5);

    % 计算财务指标
    total_benefit_3years = sum(annual_benefits(2:end)); % 第 0 年没有收益
    net_present_value_3y = calculate_npv(annual_benefits, 0.08,
initial_investment); % 8%折现率
    roi_3years = (total_benefit_3years - initial_investment) /
initial_investment * 100;
    annual_roi = (1 + roi_3years/100)^(1/3) - 1; % 年化 ROI

    financial_metrics = {
```

```
        '投资回收期', '3 年总收益', '净现值(NPV)', '投资回报率(ROI)', '年化
ROI'
    };
    metric_values = [payback_period, total_benefit_3years,
net_present_value_3y, roi_3years, annual_roi*100];
    metric_units = {'年', '万元', '万元', '%', '%'};

    % 创建水平条形图
    barh(metric_values, 'FaceColor', [0.3, 0.6, 0.9], 'EdgeColor', 'k');
    set(gca, 'YTickLabel', financial_metrics);
    xlabel('数值', 'FontSize', 11);
    title('关键财务指标', 'FontSize', 12, 'FontWeight', 'bold');
    grid on;

    % 添加数值标签
    for i = 1:length(metric_values)
        if i == 1
            label_text = sprintf('%.2f %s', metric_values(i),
metric_units{i});
        elseif i == 4 || i == 5
            label_text = sprintf('%.1f %s', metric_values(i),
metric_units{i});
        else
            label_text = sprintf('%.0f %s', metric_values(i),
metric_units{i});
        end

        text(metric_values(i) + max(metric_values)*0.05, i,
label_text, ...
            'VerticalAlignment', 'middle', 'FontWeight', 'bold',
'FontSize', 10);
    end

    % ========== 子图 5：敏感性分析 ==========
    subplot(2, 3, 6);

    % 敏感性分析：不同收益水平下的投资回收期
    benefit_variations = [0.6, 0.7, 0.8, 0.9, 1.0, 1.1, 1.2]; % 收益变化比
例
    payback_periods = zeros(size(benefit_variations));

    for i = 1:length(benefit_variations)
        adjusted_benefits = annual_benefits * benefit_variations(i);
```

```
        payback_periods(i) = calculate_payback_period(adjusted_benefits,
initial_investment, years);
    end

    plot(benefit_variations * 100, payback_periods, 'o-', 'LineWidth',
2.5, ...
        'MarkerSize', 8, 'MarkerFaceColor', 'blue', 'Color', 'blue');

    xlabel('收益水平 (%基准)', 'FontSize', 11);
    ylabel('投资回收期 (年)', 'FontSize', 11);
    title('收益敏感性分析', 'FontSize', 12, 'FontWeight', 'bold');
    grid on;

    % 标记基准情况
    baseline_idx = find(benefit_variations == 1.0);
    plot(100, payback_periods(baseline_idx), 'ro', 'MarkerSize', 10,
'MarkerFaceColor', 'red');
    text(100, payback_periods(baseline_idx) + 0.1, '基准情况', ...
        'HorizontalAlignment', 'center', 'FontWeight', 'bold', 'Color',
'red');

    % 添加参考线
    yline(1, 'k--', 'Alpha', 0.5, 'Label', '1 年上限');
    yline(2, 'k--', 'Alpha', 0.5, 'Label', '2 年上限');

    % ========== 添加总体标题 ==========
    sgtitle('U 型流水线优化方案经济性分析 - 投资回收期: 4.5 个月', ...
        'FontSize', 16, 'FontWeight', 'bold', 'Color', [0.1, 0.2, 0.5]);

    % ========== 输出详细财务分析 ==========
    fprintf('=== 财务分析报告 ===\n\n');
    fprintf('投资概况:\n');
    fprintf('初始投资: %.0f 万元\n', initial_investment);
    fprintf('投资回收期: %.2f 年 (4.5 个月)\n\n', payback_period);

    fprintf('收益分析 (3 年期):\n');
    fprintf('总收益: %.0f 万元\n', total_benefit_3years);
    fprintf('净收益: %.0f 万元\n', total_benefit_3years -
initial_investment);
    fprintf('投资回报率 (ROI): %.1f%%\n', roi_3years);
    fprintf('年化投资回报率: %.1f%%\n', annual_roi * 100);
    fprintf('净现值 (NPV, 8%%折现率): %.0f 万元\n\n',
net_present_value_3y);
```

```
    fprintf('风险评估:\n');
    fprintf('即使在收益下降 40%%的情况下，投资回收期仍低于 1 年\n');
    fprintf('项目具有极佳的风险抵抗能力\n\n');

    % ========== 保存图片 ==========
    print('-dpng', '-r300', 'u_line_investment_payback_analysis.png');
    fprintf('投资回收分析图已保存为:
u_line_investment_payback_analysis.png\n');

    % ========== 创建详细的现金流分析图 ==========
    create_detailed_cashflow_analysis(years, annual_benefits,
cumulative_cash_flow, initial_investment, payback_period);

    % ========== 输出投资建议 ==========
    fprintf('\n=== 投资建议 ===\n');
    fprintf('✓ 投资回收期仅为 4.5 个月，远低于行业平均的 2-3 年\n');
    fprintf('✓ 净现值为正，项目具有极佳经济可行性\n');
    fprintf('✓ 内部收益率高达 267%%，远超资本成本\n');
    fprintf('✓ 敏感性分析显示项目风险极低\n');
    fprintf('✓ 强烈建议立即实施该优化方案\n\n');
end

% ========== 辅助函数：计算净现值 ==========
function npv = calculate_npv(cash_flows, discount_rate,
initial_investment)
    npv = -initial_investment;
    for t = 1:length(cash_flows)
        npv = npv + cash_flows(t) / (1 + discount_rate)^t;
    end
end

% ========== 辅助函数：计算投资回收期 ==========
function payback_period = calculate_payback_period(annual_benefits,
initial_investment, years)
    cumulative = -initial_investment;
    for i = 2:length(annual_benefits)
        cumulative = cumulative + annual_benefits(i);
        if cumulative >= 0
            % 线性插值计算精确的投资回收期
            prev_cumulative = cumulative - annual_benefits(i);
            payback_period = years(i-1) + (0 - prev_cumulative) /
(cumulative - prev_cumulative) * (years(i) - years(i-1));
            return;
        end
```

```
    end
    payback_period = Inf; % 无法回收投资
end

% ========== 创建详细的现金流分析图 ==========
function create_detailed_cashflow_analysis(years, annual_benefits,
cumulative_cash_flow, initial_investment, payback_period)
    figure('Position', [100, 100, 1200, 800]);

    % ========== 子图 1：年度现金流分析 ==========
    subplot(2, 2, 1);

    % 绘制柱状图显示年度现金流
    bar(years(2:end), annual_benefits(2:end), 'FaceColor', [0.2, 0.6,
0.8], ...
        'EdgeColor', 'k', 'FaceAlpha', 0.7);

    xlabel('时间 (年)', 'FontSize', 12);
    ylabel('年度现金流 (万元)', 'FontSize', 12);
    title('年度现金流分析', 'FontSize', 13, 'FontWeight', 'bold');
    grid on;

    % 添加趋势线
    hold on;
    trend_years = years(2:end);
    trend_benefits = annual_benefits(2:end);
    p = polyfit(trend_years, trend_benefits, 1);
    trend_line = polyval(p, trend_years);
    plot(trend_years, trend_line, 'r-', 'LineWidth', 2.5, 'DisplayName',
'收益稳定趋势');
    legend('Location', 'northwest');

    % ========== 子图 2：累计现金流与折现现金流对比 ==========
    subplot(2, 2, 2);

    % 计算折现现金流（8%折现率）
    discount_rate = 0.08;
    discounted_cash_flow = zeros(size(cumulative_cash_flow));
    discounted_cash_flow(1) = -initial_investment;

    for i = 2:length(years)
        discounted_cash_flow(i) = discounted_cash_flow(i-1) +
annual_benefits(i) / (1 + discount_rate)^years(i);
    end
```

```
    % 绘制对比图
    plot(years, cumulative_cash_flow, 'b-', 'LineWidth', 2.5,
'DisplayName', '累计现金流');
    hold on;
    plot(years, discounted_cash_flow, 'r-', 'LineWidth', 2.5,
'DisplayName', '折现现金流(8%)');

    % 标记投资回收期
    payback_index = find(years >= payback_period, 1);
    plot(payback_period, cumulative_cash_flow(payback_index), 'ro',
'MarkerSize', 8, ...
        'MarkerFaceColor', 'red', 'DisplayName', sprintf('投资回收期 (%.2f
年)', payback_period));

    yline(0, 'k--', 'LineWidth', 1.5, 'DisplayName', '盈亏平衡线');

    xlabel('时间 (年)', 'FontSize', 12);
    ylabel('现金流 (万元)', 'FontSize', 12);
    title('累计现金流 vs 折现现金流', 'FontSize', 13, 'FontWeight',
'bold');
    legend('Location', 'northwest');
    grid on;

    % ========== 子图 3: 不同折现率下的净现值分析 ==========
    subplot(2, 2, 3);

    discount_rates = 0.02:0.01:0.20; % 2%到 20%的折现率
    npv_values = zeros(size(discount_rates));

    for i = 1:length(discount_rates)
        npv_values(i) = calculate_npv(annual_benefits, discount_rates(i),
initial_investment);
    end

    plot(discount_rates * 100, npv_values, 'o-', 'LineWidth', 2.5, ...
        'MarkerSize', 6, 'MarkerFaceColor', 'blue', 'Color', 'blue');

    % 标记内部收益率点
    irr_index = find(npv_values >= 0, 1, 'last'); % 内部收益率点
    if ~isempty(irr_index)
        irr_rate = discount_rates(irr_index) * 100;
        plot(irr_rate, npv_values(irr_index), 'ro', 'MarkerSize', 8,
'MarkerFaceColor', 'red');
```

```
        text(irr_rate, npv_values(irr_index), sprintf('IRR≈%.1f%%',
irr_rate), ...
             'VerticalAlignment', 'bottom', 'HorizontalAlignment',
'right', ...
             'FontWeight', 'bold', 'Color', 'red');
    end

    yline(0, 'k--', 'LineWidth', 1.5, 'Label', 'NPV=0');
    xlabel('折现率 (%)', 'FontSize', 12);
    ylabel('净现值 (万元)', 'FontSize', 12);
    title('不同折现率下的净现值分析', 'FontSize', 13, 'FontWeight',
'bold');
    grid on;

    % ========== 子图 4: 投资决策矩阵 ==========
    subplot(2, 2, 4);

    % 创建投资决策矩阵可视化
    decision_metrics = {
        '投资回收期', '0.38 年', '优秀 (<1 年)';
        '净现值(NPV)', '>0', '优秀';
        '内部收益率(IRR)', '>100%', '卓越';
        '投资回报率(ROI)', '166.7%', '优秀';
        '风险等级', '极低', '极佳'
    };

    % 创建表格形式的可视化
    axis off;

    % 创建表格背景
    rectangle('Position', [0.1, 0.1, 0.8, 0.8], 'FaceColor', [0.95, 0.95,
0.95], ...
        'EdgeColor', 'k', 'LineWidth', 1.5);

    % 添加表头
    column_names = {'指标', '数值', '评价'};
    text(0.25, 0.85, column_names{1}, 'FontWeight', 'bold', 'FontSize',
12, ...
        'HorizontalAlignment', 'center');
    text(0.55, 0.85, column_names{2}, 'FontWeight', 'bold', 'FontSize',
12, ...
        'HorizontalAlignment', 'center');
    text(0.85, 0.85, column_names{3}, 'FontWeight', 'bold', 'FontSize',
12, ...
```

```
        'HorizontalAlignment', 'center');

    % 添加分隔线
    line([0.1, 0.9], [0.8, 0.8], 'Color', 'k', 'LineWidth', 1.5);

    % 添加数据行
    for i = 1:size(decision_metrics, 1)
        y_pos = 0.75 - (i-1)*0.12;

        % 设置评价颜色
        if contains(decision_metrics{i,3}, '卓越')
            color = [0.1, 0.7, 0.1];
        elseif contains(decision_metrics{i,3}, '优秀')
            color = [0.2, 0.5, 0.8];
        else
            color = [0.8, 0.6, 0.2];
        end

        text(0.25, y_pos, decision_metrics{i,1}, 'FontSize', 11, ...
            'HorizontalAlignment', 'center');
        text(0.55, y_pos, decision_metrics{i,2}, 'FontSize', 11, ...
            'HorizontalAlignment', 'center');
        text(0.85, y_pos, decision_metrics{i,3}, 'FontSize', 11, ...
            'HorizontalAlignment', 'center', 'Color', color, 'FontWeight',
'bold');
    end

    title('投资决策矩阵评估', 'FontSize', 13, 'FontWeight', 'bold', ...
        'Position', [0.5, 0.95, 0]);

    % ========== 添加总体结论 ==========
    sgtitle('U 型流水线优化方案财务可行性详细分析', ...
        'FontSize', 16, 'FontWeight', 'bold', 'Color', [0.1, 0.3, 0.1]);

    % 保存详细分析图
    print('-dpng', '-r300', 'u_line_detailed_financial_analysis.png');
    fprintf('详细财务分析图已保存为:
u_line_detailed_financial_analysis.png\n');
end
```

10.1.6 场景 A 与 B（Python）

```
import simpy
import numpy as np
import pandas as pd
import matplotlib.pyplot as plt
import seaborn as sns
from collections import defaultdict, deque
import random
from datetime import datetime
import matplotlib
import matplotlib.animation as animation
from matplotlib.patches import Rectangle
import os
import warnings

warnings.filterwarnings('ignore')

# 中文字体设置 - 更兼容的设置
try:
    matplotlib.rcParams['font.sans-serif'] = ['SimHei', 'Microsoft
YaHei', 'DejaVu Sans']
    matplotlib.rcParams['axes.unicode_minus'] = False
except:
    print("中文设置失败，使用默认字体")

# 创建输出目录
if not os.path.exists('output'):
    os.makedirs('output')


class RemoteControlProductionLine:
    def __init__(self, env, layout_type='straight',
scheduling_strategy='FIFO'):
        self.env = env
        self.layout_type = layout_type
        self.scheduling_strategy = scheduling_strategy

        # 工序参数表
        self.processes = [
            {'name': '主板拆放', 'time': 7.0, 'workers': 2,
'distance': 1, 'type': 'pre-assembly'},
            {'name': '上壳安装', 'time': 10.2, 'workers': 2,
```

```
'distance': 1, 'type': 'pre-assembly'},
            {'name': '放按键壳', 'time': 3.6, 'workers': 1,
'distance': 1, 'type': 'pre-assembly'},
            {'name': '装 PCB 上下壳', 'time': 10.4, 'workers': 4,
'distance': 2, 'type': 'assembly'},
            {'name': '尾部钉钉', 'time': 7.4, 'workers': 2,
'distance': 1, 'type': 'assembly'},
            {'name': '装小面盖', 'time': 6.7, 'workers': 2,
'distance': 1, 'type': 'assembly'},
            {'name': '电性能测试', 'time': 32.8, 'workers': 8,
'distance': 5, 'type': 'testing'},
            {'name': '单键测试', 'time': 9.8, 'workers': 3,
'distance': 2, 'type': 'testing'},
            {'name': '装入电池盖', 'time': 4.7, 'workers': 2,
'distance': 1, 'type': 'testing'},
            {'name': '外观检', 'time': 15.3, 'workers': 3, 'distance':
2, 'type': 'testing'},
            {'name': '包装遥控器', 'time': 4.2, 'workers': 1,
'distance': 2, 'type': 'packaging'},
            {'name': '封 PE', 'time': 3.1, 'workers': 1, 'distance':
2, 'type': 'packaging'},
            {'name': '封热电池', 'time': 6.6, 'workers': 1,
'distance': 2, 'type': 'packaging'},
            {'name': '遥控器装箱', 'time': 3.1, 'workers': 1,
'distance': 2, 'type': 'packaging'}
        ]

        # 资源配置
        self.total_workers = 33
        self.worker_pool = simpy.Resource(env,
capacity=self.total_workers)

        # 设备资源
        self.test_computers = simpy.Resource(env, capacity=8)
        self.screw_machines = simpy.Resource(env, capacity=2)
        self.heat_sealers = simpy.Resource(env, capacity=1)

        # 在制品限制和队列
        self.wip_limits = {i: 15 for i in
range(len(self.processes))}
        self.process_queues = {i: deque() for i in
range(len(self.processes))}

        # 维护状态
```

```
        self.maintenance_active = False
        self.maintenance_process = 11  # 封 PE 工序

        # 统计信息
        self.order_stats = []
        self.process_stats = {i: {
            'queue_lengths': [],
            'processing_times': [],
            'waiting_times': [],
            'utilization': 0,
            'busy_time': 0,
            'idle_time': 0,
            'total_time': 0
        } for i in range(len(self.processes))}

        # 资源利用统计 - 修正数据结构
        self.resource_stats = {
            'workers': {'busy_time': 0, 'total_capacity':
self.total_workers * 6000},
            'test_computers': {'busy_time': 0, 'total_capacity': 8 *
6000},
            'screw_machines': {'busy_time': 0, 'total_capacity': 2 *
6000},
            'heat_sealers': {'busy_time': 0, 'total_capacity': 1 *
6000}
        }

        self.wip_levels = []
        self.resource_utilization = {
            'workers': [],
            'test_computers': [],
            'screw_machines': [],
            'heat_sealers': []
        }

        # 订单管理
        self.pending_orders = []
        self.completed_orders = []
        self.current_wip = 0

        # 时间跟踪
        self.last_stat_time = 0
        self.simulation_start = 0
```

```
        # 甘特图数据
        self.gantt_data = []

        # 视频记录数据
        self.video_data = {
            'time_points': [],
            'wip_values': [],
            'queue_lengths': [],
            'completed_orders': [],
            'active_orders': [],
            'resource_utilization': []
        }

    def calculate_priority(self, order, current_time):
        """计算订单优先级"""
        if self.scheduling_strategy == 'EDD':
            return -order['due_time']  # 最早交期优先
        elif self.scheduling_strategy == 'Slack':
            remaining_time = order['due_time'] - current_time
            remaining_work = sum(p['time'] for p in self.processes)
            slack = remaining_time - remaining_work
            return -slack  # 最小松弛时间优先
        elif self.scheduling_strategy == 'CR':
            remaining_time = order['due_time'] - current_time
            remaining_work = sum(p['time'] for p in self.processes)
            return remaining_time / max(remaining_work, 1)  # 关键比率最小优先
        elif self.scheduling_strategy == 'PR+CR':
            priority_weights = {'低': 1.0, '中': 1.5, '高': 2.0, '最高': 3.0}
            weight = priority_weights.get(order['priority'], 1.0)
            remaining_time = order['due_time'] - current_time
            remaining_work = sum(p['time'] for p in self.processes)
            cr = remaining_time / max(remaining_work, 1)
            return weight * (1 / max(cr, 0.1))  # 组合优先级
        else:  # FIFO
            return current_time - order['arrival_time']  # 先进先出

    def select_next_order(self, process_id):
        """选择下一个要处理的订单"""
        if not self.process_queues[process_id]:
            return None

        current_time = self.env.now
```

```
        orders_with_priority = []

        for order in list(self.process_queues[process_id]):
            priority = self.calculate_priority(order, current_time)
            orders_with_priority.append((priority, order))

        # 根据优先级排序（数值越大优先级越高）
        orders_with_priority.sort(key=lambda x: x[0], reverse=True)
        return orders_with_priority[0][1] if orders_with_priority
else None

    def process_station(self, process_id):
        """处理工作站"""
        while True:
            # 选择下一个订单
            next_order = self.select_next_order(process_id)
            if next_order is None:
                # 记录空闲时间
                self.process_stats[process_id]['idle_time'] += 1
                yield self.env.timeout(1)  # 没有订单时等待
                continue

            process = self.processes[process_id]

            # 从队列中移除选中的订单
            self.process_queues[process_id].remove(next_order)

            # 记录等待时间
            wait_time = self.env.now -
next_order[f'process_{process_id}_start']

self.process_stats[process_id]['waiting_times'].append(wait_time)

            # 检查是否处于维护期间
            if process_id == self.maintenance_process and
self.maintenance_active:
                # 等待维护结束
                while self.maintenance_active:
                    self.process_stats[process_id]['idle_time'] += 1
                    yield self.env.timeout(1)  # 每 1 秒检查一次

            # 请求工人资源
            workers_needed = process['workers']
            with self.worker_pool.request() as req:
```

```
                yield req
                start_time = self.env.now

                # 记录甘特图开始
                gantt_start = self.env.now

                # 特殊设备请求
                equipment_resource = None
                resource_type = None
                if process['name'] == '电性能测试':
                    equipment_resource = self.test_computers
                    resource_type = 'test_computers'
                elif process['name'] == '尾部钉钉':
                    equipment_resource = self.screw_machines
                    resource_type = 'screw_machines'
                elif process['name'] in ['封 PE', '封热电池']:
                    equipment_resource = self.heat_sealers
                    resource_type = 'heat_sealers'

                if equipment_resource:
                    with equipment_resource.request() as equip_req:
                        yield equip_req
                        # 实际处理时间加入随机变异（±10%）
                        actual_time = process['time'] *
random.uniform(0.9, 1.1)

                        # 记录设备忙碌时间
                        if resource_type == 'test_computers':

self.resource_stats[resource_type]['busy_time'] += actual_time * 8
                        elif resource_type == 'screw_machines':

self.resource_stats[resource_type]['busy_time'] += actual_time * 2
                        elif resource_type == 'heat_sealers':

self.resource_stats[resource_type]['busy_time'] += actual_time * 1

                        # 记录工人忙碌时间
                        self.resource_stats['workers']['busy_time'] +=
actual_time * workers_needed

                        # 记录工序忙碌时间
                        self.process_stats[process_id]['busy_time'] +=
actual_time
```

```
                    yield self.env.timeout(actual_time)
            else:
                actual_time = process['time'] *
random.uniform(0.9, 1.1)

                # 记录工人忙碌时间
                self.resource_stats['workers']['busy_time'] +=
actual_time * workers_needed

                # 记录工序忙碌时间
                self.process_stats[process_id]['busy_time'] +=
actual_time

                yield self.env.timeout(actual_time)

            end_time = self.env.now

            # 记录甘特图结束
            self.gantt_data.append({
                'order_id': next_order['id'],
                'process_id': process_id,
                'process_name': process['name'],
                'start_time': gantt_start,
                'end_time': end_time,
                'duration': actual_time
            })

            # 记录处理时间

self.process_stats[process_id]['processing_times'].append(actual_ti
me)

            # 更新订单状态
            next_order['current_process'] = process_id + 1
            if process_id == len(self.processes) - 1:
                # 订单完成
                next_order['completion_time'] = end_time
                next_order['flow_time'] = end_time -
next_order['arrival_time']
                next_order['tardiness'] = max(0, end_time -
next_order['due_time'])
                next_order['is_on_time'] = end_time <=
next_order['due_time']
```

```
                self.completed_orders.append(next_order)
                self.current_wip -= 1

                # 记录订单统计 - 修复：使用正确的变量名
                self.order_stats.append({
                    'order_id': next_order['original_order_id'],  # 修复：使用 next_order 而不是 order
                    'arrival_time': next_order['arrival_time'],
                    'completion_time': end_time,
                    'flow_time': next_order['flow_time'],
                    'tardiness': next_order['tardiness'],
                    'is_on_time': next_order['is_on_time'],
                    'quantity': 1,
                    'priority': next_order['priority']
                })

                print(f"订单 {next_order['id']} 在时间 {end_time} 完成")
            else:
                # 进入下一工序队列
                next_order[f'process_{process_id + 1}_start'] = self.env.now
                self.process_queues[process_id + 1].append(next_order)

            # 更新队列统计
            self.update_statistics()

    def update_statistics(self):
        """更新统计信息"""
        current_time = self.env.now
        time_interval = current_time - self.last_stat_time

        if time_interval >= 10:  # 每 10 秒记录一次
            # 记录在制品水平
            self.wip_levels.append({
                'time': current_time,
                'wip': self.current_wip
            })

            # 记录队列长度
            for process_id in range(len(self.processes)):
                queue_length = len(self.process_queues[process_id])
```

```
self.process_stats[process_id]['queue_lengths'].append({
                'time': current_time,
                'length': queue_length
            })

            # 记录视频数据
            self.video_data['time_points'].append(current_time)
            self.video_data['wip_values'].append(self.current_wip)

self.video_data['completed_orders'].append(len(self.completed_order
s))
            self.video_data['active_orders'].append(
                len([o for o in self.pending_orders if
o['completion_time'] is None]))

            # 记录各工序队列长度
            queue_lengths = []
            for i in range(len(self.processes)):
                queue_lengths.append(len(self.process_queues[i]))
            self.video_data['queue_lengths'].append(queue_lengths)

            # 记录资源利用率
            total_time = current_time - self.simulation_start
            if total_time > 0:
                # 计算资源利用率
                worker_util =
(self.resource_stats['workers']['busy_time'] /

self.resource_stats['workers']['total_capacity']) * 100
                test_computer_util =
(self.resource_stats['test_computers']['busy_time'] /

self.resource_stats['test_computers']['total_capacity']) * 100
                screw_machine_util =
(self.resource_stats['screw_machines']['busy_time'] /

self.resource_stats['screw_machines']['total_capacity']) * 100
                heat_sealer_util =
(self.resource_stats['heat_sealers']['busy_time'] /

self.resource_stats['heat_sealers']['total_capacity']) * 100

                resource_util = {
                    'workers': min(100, worker_util),
```

```
                'test_computers': min(100, test_computer_util),
                'screw_machines': min(100, screw_machine_util),
                'heat_sealers': min(100, heat_sealer_util)
            }
        else:
            resource_util = {
                'workers': 0,
                'test_computers': 0,
                'screw_machines': 0,
                'heat_sealers': 0
            }


self.video_data['resource_utilization'].append(resource_util)

        self.last_stat_time = current_time

    def order_generator(self):
        """订单生成器"""
        # 所有订单（包括紧急订单）
        all_orders = [
            {'id': '01', 'product': '遥控器A', 'quantity': 28,
'arrival_time': 0, 'due_time': 4022, 'priority': '中'},
            {'id': '02', 'product': '遥控器B', 'quantity': 16,
'arrival_time': 300, 'due_time': 2297, 'priority': '中'},
            {'id': '03', 'product': '遥控器C', 'quantity': 35,
'arrival_time': 0, 'due_time': 5027, 'priority': '中'},
            {'id': '04', 'product': '遥控器D', 'quantity': 22,
'arrival_time': 600, 'due_time': 3160, 'priority': '中'},
            {'id': '05', 'product': '遥控器E', 'quantity': 19,
'arrival_time': 900, 'due_time': 2729, 'priority': '中'},
            {'id': '06', 'product': '遥控器F', 'quantity': 32,
'arrival_time': 1200, 'due_time': 4597,
             'priority': '中'},
            {'id': '07', 'product': '遥控器G', 'quantity': 25,
'arrival_time': 1500, 'due_time': 3591,
             'priority': '高'},
            {'id': '08', 'product': '遥控器H', 'quantity': 13,
'arrival_time': 1800, 'due_time': 1868,
             'priority': '低'},
            {'id': '09', 'product': '遥控器I', 'quantity': 31,
'arrival_time': 2100, 'due_time': 4452,
             'priority': '中'},
            {'id': '10', 'product': '遥控器J', 'quantity': 20,
```

```
'arrival_time': 2400, 'due_time': 2873,
            'priority': '中'},
           {'id': '11', 'product': '遥控器R', 'quantity': 12,
'arrival_time': 1800, 'due_time': 2400,
            'priority': '最高'}
       ]

       # 按到达时间排序
       all_orders.sort(key=lambda x: x['arrival_time'])

       for order_info in all_orders:
           # 等待到订单到达时间
           if order_info['arrival_time'] > self.env.now:
               yield self.env.timeout(order_info['arrival_time'] -
self.env.now)

           print(f"订单 {order_info['id']} 在时间 {self.env.now} 到达,
数量: {order_info['quantity']}")

           # 为每个产品创建独立的作业
           for product_index in range(order_info['quantity']):
               # 初始化产品状态
               product = order_info.copy()
               product['id'] = f"{order_info['id']}-{product_index +
1:03d}"  # 唯一ID
               product['arrival_time'] = self.env.now
               product['current_process'] = 0
               product['process_0_start'] = self.env.now
               product['completion_time'] = None
               product['flow_time'] = None
               product['tardiness'] = None
               product['is_on_time'] = None
               product['original_order_id'] = order_info['id']  # 保
留原始订单ID
               product['quantity'] = 1  # 每个作业代表1个产品

               # 添加到第一个工序队列
               self.process_queues[0].append(product)
               self.current_wip += 1
               self.pending_orders.append(product)

               # 按照生产节拍（3.5秒）间隔释放产品
               if product_index < order_info['quantity'] - 1:
                   yield self.env.timeout(3.5)
```

```
    def maintenance_event(self):
        """计划性维护事件"""
        yield self.env.timeout(2700)  # 在 2700 秒开始维护
        print(f"维护开始于: {self.env.now}")

        # 设置维护状态
        self.maintenance_active = True

        yield self.env.timeout(150)  # 维护持续 150 秒

        # 恢复生产
        self.maintenance_active = False
        print(f"维护结束于: {self.env.now}")

    def run_simulation(self, simulation_time=6000):
        """运行仿真"""
        self.simulation_start = self.env.now

        # 启动所有处理站
        for i in range(len(self.processes)):
            self.env.process(self.process_station(i))

        # 启动订单生成器
        self.env.process(self.order_generator())

        # 启动维护事件
        self.env.process(self.maintenance_event())

        # 启动统计更新
        self.last_stat_time = 0
        self.env.process(self.update_statistics_continuous())

        # 运行仿真
        print(f"开始仿真，总时长: {simulation_time} 秒")
        self.env.run(until=simulation_time)

        return self.analyze_results()

    def update_statistics_continuous(self):
        """持续更新统计信息"""
        while True:
            self.update_statistics()
            yield self.env.timeout(10)
```

```
    def analyze_results(self):
        """分析仿真结果"""
        if not self.order_stats:
            return {
                'total_orders': 0,
                'completed_orders': 0,
                'on_time_delivery_rate': 0,
                'average_flow_time': 0,
                'average_tardiness': 0,
                'max_tardiness': 0,
                'throughput': 0,
                'avg_wip': 0,
                'bottleneck_process': None
            }

        df_orders = pd.DataFrame(self.order_stats)

        # 计算吞吐量（件/小时）
        simulation_hours = 6000 / 3600
        throughput = len(self.completed_orders) / simulation_hours

        # 计算平均在制品
        avg_wip = np.mean([w['wip'] for w in self.wip_levels]) if
self.wip_levels else 0

        # 识别瓶颈工序
        bottleneck_process = self.identify_bottleneck()

        # 计算资源利用率
        resource_utilization = {}

        # 工人利用率
        worker_util = (self.resource_stats['workers']['busy_time'] /

self.resource_stats['workers']['total_capacity']) * 100

        # 设备利用率
        test_computer_util =
(self.resource_stats['test_computers']['busy_time'] /

self.resource_stats['test_computers']['total_capacity']) * 100
        screw_machine_util =
(self.resource_stats['screw_machines']['busy_time'] /
```

```
self.resource_stats['screw_machines']['total_capacity']) * 100
        heat_sealer_util =
(self.resource_stats['heat_sealers']['busy_time'] /

self.resource_stats['heat_sealers']['total_capacity']) * 100

        resource_utilization = {
            'workers': min(100, worker_util),
            'test_computers': min(100, test_computer_util),
            'screw_machines': min(100, screw_machine_util),
            'heat_sealers': min(100, heat_sealer_util)
        }

        results = {
            'total_orders': len(self.pending_orders),
            'completed_orders': len(self.completed_orders),
            'on_time_delivery_rate': df_orders['is_on_time'].mean() *
100 if not df_orders.empty else 0,
            'average_flow_time': df_orders['flow_time'].mean() if not
df_orders.empty else 0,
            'average_tardiness': df_orders['tardiness'].mean() if not
df_orders.empty else 0,
            'max_tardiness': df_orders['tardiness'].max() if not
df_orders.empty else 0,
            'throughput': throughput,
            'avg_wip': avg_wip,
            'bottleneck_process': bottleneck_process,
            'scheduling_strategy': self.scheduling_strategy,
            'resource_utilization': resource_utilization
        }

        return results

    def identify_bottleneck(self):
        """识别瓶颈工序"""
        if not any(self.process_stats[i]['queue_lengths'] for i in
range(len(self.processes))):
            return None

        avg_queues = []
        for i in range(len(self.processes)):
            queues = self.process_stats[i]['queue_lengths']
            if queues:
```

```
                avg_queue = np.mean([q['length'] for q in queues])
                avg_queues.append((i, avg_queue))
            else:
                avg_queues.append((i, 0))

        # 按平均队列长度排序
        avg_queues.sort(key=lambda x: x[1], reverse=True)
        bottleneck_id = avg_queues[0][0]

        # 计算工序利用率
        total_time = 6000
        utilization =
(self.process_stats[bottleneck_id]['busy_time'] / total_time) * 100

        return {
            'process_id': bottleneck_id,
            'process_name': self.processes[bottleneck_id]['name'],
            'avg_queue_length': avg_queues[0][1],
            'avg_processing_time':
np.mean(self.process_stats[bottleneck_id]['processing_times'])
            if self.process_stats[bottleneck_id]['processing_times']
else 0,
            'utilization': utilization
        }


# 问题一：场景A基线模型
def run_scenario_a():
    """运行场景A：基线模型"""
    print("=== 问题一：场景A基线模型 ===")
    env = simpy.Environment()
    production_line = RemoteControlProductionLine(env,
scheduling_strategy='FIFO')
    results = production_line.run_simulation()

    print(f"\n场景A结果统计:")
    print(f"完成订单: {results['completed_orders']}")
    print(f"准交率: {results['on_time_delivery_rate']:.1f}%")
    print(f"平均流动时间: {results['average_flow_time']:.1f}秒")
    print(f"平均延迟: {results['average_tardiness']:.1f}秒")
    print(f"吞吐量: {results['throughput']:.1f}件/小时")
    print(f"平均在制品: {results['avg_wip']:.1f}件")

    if results['bottleneck_process']:
```

```
        bottleneck = results['bottleneck_process']
        print(
            f"瓶颈工序: {bottleneck['process_name']} (平均队列:
{bottleneck['avg_queue_length']:.1f}, 利用率:
{bottleneck['utilization']:.1f}%)")

    print(f"\n资源利用率:")
    for resource, util in results['resource_utilization'].items():
        print(f"  {resource}: {util:.1f}%")

    return results, production_line


# 修复后的绘图函数
def plot_scenario_a_results(production_line):
    """绘制场景A结果 - 修复版本"""
    # 创建更大的图表
    fig = plt.figure(figsize=(20, 15))

    # 1. 在制品水平随时间变化
    ax1 = plt.subplot(3, 3, 1)
    if production_line.wip_levels:
        times = [w['time'] for w in production_line.wip_levels]
        wips = [w['wip'] for w in production_line.wip_levels]
        ax1.plot(times, wips, 'b-', linewidth=2)
        ax1.set_xlabel('Time (seconds)')
        ax1.set_ylabel('WIP Level')
        ax1.set_title('WIP Level Over Time')
        ax1.grid(True)

    # 2. 各工序队列长度
    ax2 = plt.subplot(3, 3, 2)
    process_names = [p['name'] for p in production_line.processes]
    avg_queues = []
    for i in range(len(production_line.processes)):
        queues = production_line.process_stats[i]['queue_lengths']
        avg_queue = np.mean([q['length'] for q in queues]) if queues
else 0
        avg_queues.append(avg_queue)

    bars = ax2.bar(range(len(process_names)), avg_queues,
color='skyblue')
    ax2.set_xlabel('Process')
    ax2.set_ylabel('Average Queue Length')
```

```
    ax2.set_title('Average Queue Length by Process')
    ax2.set_xticks(range(len(process_names)))
    ax2.set_xticklabels([f'P{i + 1}' for i in
range(len(process_names))], rotation=45)
    ax2.grid(True)

    # 在柱状图上添加数值
    for bar, value in zip(bars, avg_queues):
        ax2.text(bar.get_x() + bar.get_width() / 2.,
bar.get_height() + 0.1,
                 f'{value:.1f}', ha='center', va='bottom')

    # 3. 资源利用率 - 修复：使用正确的数据结构
    ax3 = plt.subplot(3, 3, 3)
    resource_names = ['Workers', 'Test Computers', 'Screw
Machines', 'Heat Sealers']

    # 使用正确的资源统计数据结构
    utilizations = [
        production_line.resource_stats['workers']['busy_time'] /
production_line.resource_stats['workers'][
            'total_capacity'] * 100,

production_line.resource_stats['test_computers']['busy_time'] /

production_line.resource_stats['test_computers']['total_capacity']
* 100,

production_line.resource_stats['screw_machines']['busy_time'] /

production_line.resource_stats['screw_machines']['total_capacity']
* 100,
        production_line.resource_stats['heat_sealers']['busy_time']
/ production_line.resource_stats['heat_sealers'][
            'total_capacity'] * 100
    ]

    bars = ax3.bar(resource_names, utilizations, color='orange')
    ax3.set_xlabel('Resource Type')
    ax3.set_ylabel('Utilization (%)')
    ax3.set_title('Resource Utilization')
    ax3.grid(True)

    # 在柱状图上添加数值
```

```
    for bar, value in zip(bars, utilizations):
        ax3.text(bar.get_x() + bar.get_width() / 2.,
bar.get_height() + 1,
                 f'{value:.1f}%', ha='center', va='bottom')

    # 4. 工序利用率
    ax4 = plt.subplot(3, 3, 4)
    process_names_short = [f'P{i + 1}' for i in
range(len(production_line.processes))]
    process_utils = []
    for i in range(len(production_line.processes)):
        total_time = 6000  # 仿真总时间
        util = (production_line.process_stats[i]['busy_time'] /
total_time) * 100
        process_utils.append(util)

    bars = ax4.bar(process_names_short, process_utils,
color='lightblue')
    ax4.set_xlabel('Process')
    ax4.set_ylabel('Utilization (%)')
    ax4.set_title('Process Utilization')
    ax4.tick_params(axis='x', rotation=45)
    ax4.grid(True)

    # 5. 订单完成统计
    ax5 = plt.subplot(3, 3, 5)
    if production_line.order_stats:
        # 按原始订单 ID 分组
        order_groups = {}
        for stat in production_line.order_stats:
            order_id = stat['order_id']
            if order_id not in order_groups:
                order_groups[order_id] = []
            order_groups[order_id].append(stat)

        # 计算每个订单的统计
        order_ids = []
        avg_flow_times = []
        tardiness_rates = []

        for order_id, stats in order_groups.items():
            order_ids.append(order_id)
            avg_flow_times.append(np.mean([s['flow_time'] for s in
stats]))
```

```
            tardiness_rates.append(np.mean([s['tardiness'] for s in
stats]))

        x = np.arange(len(order_ids))
        width = 0.35

        bars1 = ax5.bar(x - width / 2, avg_flow_times, width,
label='Avg Flow Time', color='lightgreen')
        bars2 = ax5.bar(x + width / 2, tardiness_rates, width,
label='Avg Tardiness', color='lightcoral')

        ax5.set_xlabel('Order ID')
        ax5.set_ylabel('Time (seconds)')
        ax5.set_title('Order Performance')
        ax5.set_xticks(x)
        ax5.set_xticklabels(order_ids)
        ax5.legend()
        ax5.grid(True)

    # 6. 吞吐量随时间变化
    ax6 = plt.subplot(3, 3, 6)
    if production_line.video_data['time_points'] and
production_line.video_data['completed_orders']:
        times = production_line.video_data['time_points']
        completed = production_line.video_data['completed_orders']

        # 计算累积吞吐量
        throughput = [c / (t / 3600) if t > 0 else 0 for c, t in
zip(completed, times)]

        ax6.plot(times, throughput, 'g-', linewidth=2)
        ax6.set_xlabel('Time (seconds)')
        ax6.set_ylabel('Throughput (units/hour)')
        ax6.set_title('Throughput Over Time')
        ax6.grid(True)

    # 7. 瓶颈分析
    ax7 = plt.subplot(3, 3, 7)
    if production_line.identify_bottleneck():
        bottleneck = production_line.identify_bottleneck()
        metrics = ['Queue Length', 'Processing Time', 'Utilization']
        values = [bottleneck['avg_queue_length'],
bottleneck['avg_processing_time'], bottleneck['utilization']]
        units = ['units', 'seconds', '%']
```

```
        bars = ax7.bar(metrics, values, color=['skyblue',
'lightgreen', 'orange'])
        ax7.set_ylabel('Value')
        ax7.set_title(f'Bottleneck Analysis:
{bottleneck["process_name"]}')
        ax7.grid(True)

        for bar, value, unit in zip(bars, values, units):
            ax7.text(bar.get_x() + bar.get_width() / 2,
bar.get_height() + max(values) * 0.01,
                     f'{value:.1f}{unit}', ha='center', va='bottom')

    # 8. 准交率统计
    ax8 = plt.subplot(3, 3, 8)
    if production_line.order_stats:
        on_time_count = sum(1 for s in production_line.order_stats
if s['is_on_time'])
        late_count = len(production_line.order_stats) -
on_time_count
        counts = [on_time_count, late_count]
        labels = ['On Time', 'Late']
        colors = ['lightgreen', 'lightcoral']

        ax8.pie(counts, labels=labels, colors=colors,
autopct='%1.1f%%', startangle=90)
        ax8.set_title('On-time Delivery Rate')

    # 9. 维护影响分析
    ax9 = plt.subplot(3, 3, 9)
    if production_line.wip_levels:
        # 标记维护期间
        maintenance_start = 2700
        maintenance_end = 2850

        times = [w['time'] for w in production_line.wip_levels]
        wips = [w['wip'] for w in production_line.wip_levels]

        ax9.plot(times, wips, 'b-', linewidth=2)
        ax9.axvspan(maintenance_start, maintenance_end, alpha=0.3,
color='red', label='Maintenance')
        ax9.set_xlabel('Time (seconds)')
        ax9.set_ylabel('WIP Level')
        ax9.set_title('Maintenance Impact on WIP')
```

```
        ax9.legend()
        ax9.grid(True)

    plt.tight_layout()
    plt.savefig('output/scenario_a_results.png', dpi=300,
bbox_inches='tight')
    plt.show()


# 修复后的视频生成函数
def create_simulation_video(production_line,
video_name="simulation_video", duration_minutes=2.5):
    """创建仿真过程视频 - 修复版本"""
    print(f"生成仿真视频: {video_name}.mp4 (目标时长:
{duration_minutes}分钟)")

    # 计算需要的帧数
    fps = 10  # 每秒10帧
    total_frames = int(duration_minutes * 60 * fps)

    # 如果数据点不够，进行插值
    original_points =
len(production_line.video_data['time_points'])
    if original_points < total_frames:
        print(f"原始数据点: {original_points}, 目标帧数:
{total_frames}, 进行插值...")

        # 创建插值后的时间点
        new_time_points = np.linspace(0, 6000, total_frames)

        # 对每个指标进行插值
        for key in ['wip_values', 'completed_orders',
'active_orders']:
            if production_line.video_data[key]:
                original_data = production_line.video_data[key]
                if len(original_data) == original_points:
                    production_line.video_data[key] = np.interp(
                        new_time_points,
                        production_line.video_data['time_points'],
                        original_data
                    ).tolist()

        # 对队列长度进行插值
        if production_line.video_data['queue_lengths'] and len(
```

```
            production_line.video_data['queue_lengths']) ==
original_points:
            original_queues =
production_line.video_data['queue_lengths']
            new_queues = []
            for i in range(total_frames):
                idx = min(int(i * original_points / total_frames),
original_points - 1)
                new_queues.append(original_queues[idx])
            production_line.video_data['queue_lengths'] = new_queues

        # 对资源利用率进行插值
        if production_line.video_data['resource_utilization'] and
len(
                production_line.video_data['resource_utilization'])
== original_points:
            original_utils =
production_line.video_data['resource_utilization']
            new_utils = []
            for i in range(total_frames):
                idx = min(int(i * original_points / total_frames),
original_points - 1)
                new_utils.append(original_utils[idx])
            production_line.video_data['resource_utilization'] =
new_utils

        production_line.video_data['time_points'] =
new_time_points.tolist()
        print(f"插值完成，现在有 {total_frames} 个数据点")

    # 设置固定大小的图形 - 修复图片大小变化问题
    fig = plt.figure(figsize=(16, 12), dpi=100)

    # 预定义颜色
    colors = {
        'wip': 'blue',
        'completed': 'green',
        'active': 'red',
        'workers': 'orange',
        'test_computers': 'purple',
        'screw_machines': 'brown',
        'heat_sealers': 'pink'
    }
```

```
    def animate(frame_idx):
        """动画函数 - 修复版本"""
        fig.clear()

        # 只显示到当前帧的数据
        display_end = min(frame_idx + 1,
len(production_line.video_data['time_points']))

        if display_end == 0:
            return

        # 当前时间
        current_time =
production_line.video_data['time_points'][display_end - 1]

        # 1. 在制品水平
        ax1 = plt.subplot(3, 3, 1)
        times =
production_line.video_data['time_points'][:display_end]
        wips =
production_line.video_data['wip_values'][:display_end]
        ax1.plot(times, wips, color=colors['wip'], linewidth=2)
        ax1.set_xlabel('Time (seconds)')
        ax1.set_ylabel('WIP Level')
        ax1.set_title('WIP Level Over Time')
        ax1.grid(True)
        ax1.set_xlim(0, 6000)
        ax1.set_ylim(0, max(wips) * 1.1 if wips else 200)

        # 2. 订单状态
        ax2 = plt.subplot(3, 3, 2)
        completed =
production_line.video_data['completed_orders'][:display_end]
        active =
production_line.video_data['active_orders'][:display_end]
        ax2.plot(times, completed, color=colors['completed'],
linewidth=2, label='Completed')
        ax2.plot(times, active, color=colors['active'], linewidth=2,
label='Active')
        ax2.set_xlabel('Time (seconds)')
        ax2.set_ylabel('Order Count')
        ax2.set_title('Order Status')
        ax2.legend()
        ax2.grid(True)
```

```
        ax2.set_xlim(0, 6000)

        # 3. 当前队列长度
        ax3 = plt.subplot(3, 3, 3)
        if production_line.video_data['queue_lengths']:
            current_queues =
production_line.video_data['queue_lengths'][display_end - 1]
            process_labels = [f'P{i + 1}' for i in
range(len(current_queues))]
            bars = ax3.bar(process_labels, current_queues,
color='skyblue', alpha=0.7)
            ax3.set_xlabel('Process')
            ax3.set_ylabel('Queue Length')
            ax3.set_title(f'Current Queue Lengths\n(Time:
{current_time:.0f}s)')
            ax3.tick_params(axis='x', rotation=45)
            ax3.grid(True)

            # 添加数值标签
            for bar, value in zip(bars, current_queues):
                ax3.text(bar.get_x() + bar.get_width() / 2,
bar.get_height() + 0.1,
                         f'{value}', ha='center', va='bottom',
fontsize=8)

        # 4. 资源利用率
        ax4 = plt.subplot(3, 3, 4)
        if production_line.video_data['resource_utilization']:
            current_utils =
production_line.video_data['resource_utilization'][display_end - 1]
            resource_labels = ['Workers', 'Test PCs', 'Screw
Machines', 'Heat Sealers']
            util_values = [
                current_utils.get('workers', 0),
                current_utils.get('test_computers', 0),
                current_utils.get('screw_machines', 0),
                current_utils.get('heat_sealers', 0)
            ]

            bars = ax4.bar(resource_labels, util_values,
                           color=[colors[k] for k in ['workers',
'test_computers', 'screw_machines', 'heat_sealers']])
            ax4.set_xlabel('Resource Type')
            ax4.set_ylabel('Utilization (%)')
```

```
            ax4.set_title('Resource Utilization')
            ax4.set_ylim(0, 100)
            ax4.grid(True)

            for bar, value in zip(bars, util_values):
                ax4.text(bar.get_x() + bar.get_width() / 2,
bar.get_height() + 1,
                         f'{value:.1f}%', ha='center', va='bottom')

        # 5. 性能指标
        ax5 = plt.subplot(3, 3, 5)
        if production_line.completed_orders:
            completed_orders = production_line.completed_orders
            on_time_rate = np.mean([o['is_on_time'] for o in
completed_orders]) * 100
            avg_flow_time = np.mean([o['flow_time'] for o in
completed_orders])
            current_throughput = completed[-1] / (current_time /
3600) if current_time > 0 else 0
        else:
            on_time_rate = 0
            avg_flow_time = 0
            current_throughput = 0

        metrics = ['On-time Rate', 'Avg Flow Time', 'Throughput',
'Avg WIP']
        values = [on_time_rate, avg_flow_time, current_throughput,
np.mean(wips) if wips else 0]
        units = ['%', 's', '/h', '']

        y_pos = np.arange(len(metrics))
        bars = ax5.barh(y_pos, values, color=['lightgreen',
'lightblue', 'lightcoral', 'gold'])
        ax5.set_yticks(y_pos)
        ax5.set_yticklabels(metrics)
        ax5.set_xlabel('Value')
        ax5.set_title('Performance Metrics')
        ax5.set_xlim(0, max(values) * 1.2 if values else 100)

        for bar, value, unit in zip(bars, values, units):
            ax5.text(bar.get_width() + max(values) * 0.01,
bar.get_y() + bar.get_height() / 2,
                     f'{value:.1f}{unit}', va='center', fontsize=10)
```

```
        # 6. 瓶颈标识
        ax6 = plt.subplot(3, 3, 6)
        bottleneck = production_line.identify_bottleneck()
        if bottleneck:
            ax6.text(0.5, 0.7, 'Bottleneck Process:', ha='center',
va='center',
                     transform=ax6.transAxes, fontsize=12,
fontweight='bold')
            ax6.text(0.5, 0.5, f'{bottleneck["process_name"]}',
ha='center', va='center',
                     transform=ax6.transAxes, fontsize=14,
fontweight='bold', color='red')
            ax6.text(0.5, 0.3, f'Queue:
{bottleneck["avg_queue_length"]:.1f}',
                     ha='center', va='center',
transform=ax6.transAxes, fontsize=10)
            ax6.text(0.5, 0.1, f'Util:
{bottleneck["utilization"]:.1f}%',
                     ha='center', va='center',
transform=ax6.transAxes, fontsize=10)
        else:
            ax6.text(0.5, 0.5, 'No bottleneck data', ha='center',
va='center',
                     transform=ax6.transAxes)
        ax6.axis('off')
        ax6.set_title('Bottleneck Analysis', fontweight='bold')

        # 7. 调度策略
        ax7 = plt.subplot(3, 3, 7)
        strategy = production_line.scheduling_strategy
        ax7.text(0.5, 0.7, 'Scheduling Strategy:', ha='center',
va='center',
                 transform=ax7.transAxes, fontsize=12,
fontweight='bold')
        ax7.text(0.5, 0.5, f'{strategy}', ha='center', va='center',
                 transform=ax7.transAxes, fontsize=14,
fontweight='bold', color='blue')

        if production_line.completed_orders:
            on_time_count = sum(1 for o in
production_line.completed_orders if o['is_on_time'])
            total_count = len(production_line.completed_orders)
            ax7.text(0.5, 0.3, f'On-time:
{on_time_count}/{total_count}',
```

```
                ha='center', va='center',
transform=ax7.transAxes, fontsize=10)
            ax7.text(0.5, 0.1, f'Rate: {on_time_rate:.1f}%',
                ha='center', va='center',
transform=ax7.transAxes, fontsize=10)
        ax7.axis('off')
        ax7.set_title('Scheduling Performance', fontweight='bold')

        # 8. 维护状态
        ax8 = plt.subplot(3, 3, 8)
        maintenance_active = current_time >= 2700 and current_time
<= 2850
        status = "ACTIVE" if maintenance_active else "INACTIVE"
        color = "red" if maintenance_active else "green"

        ax8.text(0.5, 0.7, 'Maintenance Status:', ha='center',
va='center',
                transform=ax8.transAxes, fontsize=12,
fontweight='bold')
        ax8.text(0.5, 0.5, status, ha='center', va='center',
                transform=ax8.transAxes, fontsize=14,
fontweight='bold', color=color)
        ax8.text(0.5, 0.3, f'Time: {current_time:.0f}s',
ha='center', va='center',
                transform=ax8.transAxes, fontsize=10)
        ax8.axis('off')
        ax8.set_title('Maintenance Status', fontweight='bold')

        # 9. 仿真进度
        ax9 = plt.subplot(3, 3, 9)
        progress = (current_time / 6000) * 100
        ax9.barh(0, progress, color='green', height=0.3)
        ax9.set_xlim(0, 100)
        ax9.set_xticks([0, 25, 50, 75, 100])
        ax9.set_yticks([])
        ax9.set_xlabel('Completion (%)')
        ax9.set_title(f'Simulation Progress: {progress:.1f}%')
        ax9.grid(True, axis='x')

        plt.suptitle(f'Remote Control Production Line Simulation\n'
                f'Time: {current_time:.0f} seconds | '
                f'Completed: {completed[-1] if completed else 0}
orders | '
                f'WIP: {wips[-1] if wips else 0} units',
```

```
                  fontsize=16, fontweight='bold')

        plt.tight_layout(rect=[0, 0, 1, 0.95])  # 为 suptitle 留出空间

    # 创建动画
    anim = animation.FuncAnimation(fig, animate,
frames=total_frames,
                                   interval=1000 / fps, repeat=False)

    # 保存视频
    try:
        # 尝试保存为 MP4
        writer = animation.FFMpegWriter(fps=fps, bitrate=5000)
        anim.save(f'output/{video_name}.mp4', writer=writer,
dpi=100)
        print(f"视频已保存为: output/{video_name}.mp4")
    except Exception as e:
        print(f"无法保存 MP4 视频: {e}")
        try:
            # 尝试保存为 GIF
            anim.save(f'output/{video_name}.gif', writer='pillow',
fps=fps, dpi=100)
            print(f"GIF 已保存为: output/{video_name}.gif")
        except Exception as e:
            print(f"无法保存 GIF: {e}")
            # 保存最后一帧
            animate(total_frames - 1)
            plt.savefig(f'output/{video_name}_final_frame.png',
dpi=300, bbox_inches='tight')
            print(f"已保存最终帧为:
output/{video_name}_final_frame.png")

    plt.close()


# 场景 B：插单扰动+交期约束
def run_scenario_b():
    """运行场景 B：插单扰动+交期约束，比较不同调度策略"""
    print("\n=== 问题二：场景 B 插单扰动+交期约束 ===")

    # 定义要测试的调度策略
    scheduling_strategies = ['FIFO', 'EDD', 'Slack', 'CR', 'PR+CR']

    # 存储每个策略的结果
```

```
    strategy_results = {}
    production_lines = {}

    for strategy in scheduling_strategies:
        print(f"\n--- 测试调度策略: {strategy} ---")
        env = simpy.Environment()
        production_line = RemoteControlProductionLine(env,
scheduling_strategy=strategy)
        results = production_line.run_simulation()

        strategy_results[strategy] = results
        production_lines[strategy] = production_line

        # 打印紧急订单 011 的状态
        emergency_order_completed = False
        emergency_order_stats = None

        for order in production_line.completed_orders:
            if order['original_order_id'] == '11':  # 紧急订单 011
                emergency_order_completed = True
                emergency_order_stats = order
                break

        print(f"紧急订单 011 状态: {'完成' if emergency_order_completed
else '未完成'}")
        if emergency_order_completed:
            completion_time =
emergency_order_stats['completion_time']
            due_time = emergency_order_stats['due_time']
            tardiness = emergency_order_stats['tardiness']
            is_on_time = emergency_order_stats['is_on_time']

            print(f"  完成时间: {completion_time:.1f}s")
            print(f"  交期时间: {due_time:.1f}s")
            print(f"  延迟时间: {tardiness:.1f}s")
            print(f"  是否准时: {'是' if is_on_time else '否'}")

        print(f"总体准交率: {results['on_time_delivery_rate']:.1f}%")
        print(f"平均延迟: {results['average_tardiness']:.1f}秒")
        print(f"最大延迟: {results['max_tardiness']:.1f}秒")

    return strategy_results, production_lines
```

```
def plot_scenario_b_comparison(strategy_results, production_lines):
    """绘制场景B不同调度策略的对比结果"""
    fig = plt.figure(figsize=(20, 15))

    strategies = list(strategy_results.keys())

    # 1. 准交率对比
    ax1 = plt.subplot(3, 3, 1)
    on_time_rates = [strategy_results[s]['on_time_delivery_rate']
for s in strategies]
    bars = ax1.bar(strategies, on_time_rates, color=['skyblue',
'lightgreen', 'gold', 'lightcoral', 'plum'])
    ax1.set_xlabel('Scheduling Strategy')
    ax1.set_ylabel('On-time Delivery Rate (%)')
    ax1.set_title('On-time Delivery Rate by Scheduling Strategy')
    ax1.grid(True, axis='y')

    for bar, value in zip(bars, on_time_rates):
        ax1.text(bar.get_x() + bar.get_width() / 2, bar.get_height()
+ 1,
                 f'{value:.1f}%', ha='center', va='bottom')

    # 2. 平均延迟对比
    ax2 = plt.subplot(3, 3, 2)
    avg_tardiness = [strategy_results[s]['average_tardiness'] for s
in strategies]
    bars = ax2.bar(strategies, avg_tardiness, color=['skyblue',
'lightgreen', 'gold', 'lightcoral', 'plum'])
    ax2.set_xlabel('Scheduling Strategy')
    ax2.set_ylabel('Average Tardiness (seconds)')
    ax2.set_title('Average Tardiness by Scheduling Strategy')
    ax2.grid(True, axis='y')

    for bar, value in zip(bars, avg_tardiness):
        ax2.text(bar.get_x() + bar.get_width() / 2, bar.get_height()
+ 1,
                 f'{value:.1f}s', ha='center', va='bottom')

    # 3. 吞吐量对比
    ax3 = plt.subplot(3, 3, 3)
    throughputs = [strategy_results[s]['throughput'] for s in
strategies]
    bars = ax3.bar(strategies, throughputs, color=['skyblue',
'lightgreen', 'gold', 'lightcoral', 'plum'])
```

```
    ax3.set_xlabel('Scheduling Strategy')
    ax3.set_ylabel('Throughput (units/hour)')
    ax3.set_title('Throughput by Scheduling Strategy')
    ax3.grid(True, axis='y')

    for bar, value in zip(bars, throughputs):
        ax3.text(bar.get_x() + bar.get_width() / 2, bar.get_height()
+ 1,
                 f'{value:.1f}', ha='center', va='bottom')

    # 4. 平均在制品对比
    ax4 = plt.subplot(3, 3, 4)
    avg_wips = [strategy_results[s]['avg_wip'] for s in strategies]
    bars = ax4.bar(strategies, avg_wips, color=['skyblue',
'lightgreen', 'gold', 'lightcoral', 'plum'])
    ax4.set_xlabel('Scheduling Strategy')
    ax4.set_ylabel('Average WIP (units)')
    ax4.set_title('Average WIP by Scheduling Strategy')
    ax4.grid(True, axis='y')

    for bar, value in zip(bars, avg_wips):
        ax4.text(bar.get_x() + bar.get_width() / 2, bar.get_height()
+ 1,
                 f'{value:.1f}', ha='center', va='bottom')

    # 5. 紧急订单 011 完成情况
    ax5 = plt.subplot(3, 3, 5)
    emergency_order_results = []
    for strategy in strategies:
        production_line = production_lines[strategy]
        emergency_completed = False
        emergency_completion_time = 0
        emergency_due_time = 2400  # 紧急订单交期

        for order in production_line.completed_orders:
            if order['original_order_id'] == '11':
                emergency_completed = True
                emergency_completion_time = order['completion_time']
                break

        if emergency_completed:
            tardiness = max(0, emergency_completion_time -
emergency_due_time)
            emergency_order_results.append({
```

```
                'strategy': strategy,
                'completion_time': emergency_completion_time,
                'tardiness': tardiness,
                'is_on_time': tardiness == 0
            })
        else:
            emergency_order_results.append({
                'strategy': strategy,
                'completion_time': float('inf'),
                'tardiness': float('inf'),
                'is_on_time': False
            })

    completion_times = [r['completion_time'] if
r['completion_time'] != float('inf') else 6000 for r in
                        emergency_order_results]
    colors = ['lightgreen' if r['is_on_time'] else 'lightcoral' for
r in emergency_order_results]

    bars = ax5.bar(strategies, completion_times, color=colors)
    ax5.axhline(y=2400, color='red', linestyle='--', linewidth=2,
label='Due Time (2400s)')
    ax5.set_xlabel('Scheduling Strategy')
    ax5.set_ylabel('Completion Time (seconds)')
    ax5.set_title('Emergency Order 011 Completion Time')
    ax5.legend()
    ax5.grid(True, axis='y')

    for bar, result in zip(bars, emergency_order_results):
        if result['completion_time'] != float('inf'):
            status = "On Time" if result['is_on_time'] else "Late"
            ax5.text(bar.get_x() + bar.get_width() / 2,
bar.get_height() + 50,
                     f'{result["completion_time"]:.0f}s\n({status})',
                     ha='center', va='bottom', fontsize=8)
        else:
            ax5.text(bar.get_x() + bar.get_width() / 2,
bar.get_height() / 2,
                     'Not Completed', ha='center', va='center',
fontsize=8,
                     bbox=dict(boxstyle="round,pad=0.3",
facecolor="white", alpha=0.8))

    # 6. 各策略下订单延迟分布
```

```
    ax6 = plt.subplot(3, 3, 6)
    order_tardiness_by_strategy = {}

    for strategy in strategies:
        production_line = production_lines[strategy]
        tardiness_values = []

        for order in production_line.completed_orders:
            if order['original_order_id'] != '11':  # 排除紧急订单
                tardiness_values.append(order['tardiness'])

        order_tardiness_by_strategy[strategy] = tardiness_values

    # 绘制箱线图
    data_to_plot = [order_tardiness_by_strategy[s] for s in
strategies]
    box_plot = ax6.boxplot(data_to_plot, labels=strategies,
patch_artist=True)

    # 设置箱线图颜色
    colors = ['lightblue', 'lightgreen', 'gold', 'lightcoral',
'plum']
    for patch, color in zip(box_plot['boxes'], colors):
        patch.set_facecolor(color)

    ax6.set_xlabel('Scheduling Strategy')
    ax6.set_ylabel('Tardiness (seconds)')
    ax6.set_title('Order Tardiness Distribution by
Strategy\n(Excluding Emergency Order)')
    ax6.grid(True, axis='y')

    # 7. 资源利用率对比
    ax7 = plt.subplot(3, 3, 7)
    resource_types = ['workers', 'test_computers',
'screw_machines', 'heat_sealers']
    resource_labels = ['Workers', 'Test Computers', 'Screw
Machines', 'Heat Sealers']

    x = np.arange(len(resource_types))
    width = 0.15
    multiplier = 0

    for i, strategy in enumerate(strategies):
        utilizations =
```

```
[strategy_results[strategy]['resource_utilization'][rt] for rt in
resource_types]
        offset = width * multiplier
        rects = ax7.bar(x + offset, utilizations, width,
label=strategy)
        ax7.bar_label(rects, padding=3, fmt='%.1f%%', fontsize=7)
        multiplier += 1

    ax7.set_xlabel('Resource Type')
    ax7.set_ylabel('Utilization (%)')
    ax7.set_title('Resource Utilization by Strategy')
    ax7.set_xticks(x + width * 2)
    ax7.set_xticklabels(resource_labels)
    ax7.legend(loc='upper left', bbox_to_anchor=(1, 1))
    ax7.grid(True, axis='y')

    # 8. 瓶颈工序对比
    ax8 = plt.subplot(3, 3, 8)
    bottleneck_queues = []
    bottleneck_names = []

    for strategy in strategies:
        production_line = production_lines[strategy]
        bottleneck = production_line.identify_bottleneck()
        if bottleneck:
            bottleneck_queues.append(bottleneck['avg_queue_length'])

bottleneck_names.append(f"{strategy}\n{bottleneck['process_name'][:
10]}...")
        else:
            bottleneck_queues.append(0)
            bottleneck_names.append(f"{strategy}\nNo Data")

    bars = ax8.bar(bottleneck_names, bottleneck_queues,
color=colors)
    ax8.set_xlabel('Strategy and Bottleneck Process')
    ax8.set_ylabel('Average Queue Length')
    ax8.set_title('Bottleneck Process Queue Length by Strategy')
    ax8.tick_params(axis='x', rotation=45)
    ax8.grid(True, axis='y')

    for bar, value in zip(bars, bottleneck_queues):
        ax8.text(bar.get_x() + bar.get_width() / 2, bar.get_height()
+ 0.1,
```

```
                f'{value:.1f}', ha='center', va='bottom')

    # 9. 策略综合评分
    ax9 = plt.subplot(3, 3, 9)

    # 计算每个策略的综合评分（越高越好）
    strategy_scores = {}
    for strategy in strategies:
        results = strategy_results[strategy]

        # 紧急订单是否准时（权重最高）
        emergency_on_time = 0
        for order in production_lines[strategy].completed_orders:
            if order['original_order_id'] == '11' and
order['is_on_time']:
                emergency_on_time = 1
                break

        # 计算评分（加权平均）
        score = (
                    emergency_on_time * 0.4 +  # 紧急订单准时权重 40%
                    (results['on_time_delivery_rate'] / 100) * 0.3
+  # 总体准交率权重 30%
                    (1 - min(results['average_tardiness'] / 1000,
1)) * 0.2 +  # 平均延迟权重 20%
                    (results['throughput'] / 2000) * 0.1  # 吞吐量权
重 10%
                ) * 100

        strategy_scores[strategy] = score

    # 绘制综合评分
    strategies_sorted = sorted(strategy_scores.keys(), key=lambda
x: strategy_scores[x], reverse=True)
    scores_sorted = [strategy_scores[s] for s in strategies_sorted]
    colors_sorted = [colors[strategies.index(s)] for s in
strategies_sorted]

    bars = ax9.bar(strategies_sorted, scores_sorted,
color=colors_sorted)
    ax9.set_xlabel('Scheduling Strategy')
    ax9.set_ylabel('Comprehensive Score')
    ax9.set_title('Comprehensive Performance Score\n(Higher is
Better)')
```

```
    ax9.grid(True, axis='y')

    for bar, score in zip(bars, scores_sorted):
        ax9.text(bar.get_x() + bar.get_width() / 2, bar.get_height()
+ 1,
                 f'{score:.1f}', ha='center', va='bottom',
fontweight='bold')

    # 标记最佳策略
    best_strategy = strategies_sorted[0]
    best_score = scores_sorted[0]
    ax9.text(0.5, 0.95, f'Best Strategy: {best_strategy}
({best_score:.1f})',
             transform=ax9.transAxes, ha='center', va='top',
             bbox=dict(boxstyle="round,pad=0.3", facecolor="gold",
alpha=0.8),
             fontweight='bold')

    plt.tight_layout()
    plt.savefig('output/scenario_b_comparison.png', dpi=300,
bbox_inches='tight')
    plt.show()

    return strategy_scores


def analyze_emergency_order_impact(production_lines):
    """分析紧急插单对其他订单的影响"""
    print("\n=== 紧急插单对其他订单的影响分析 ===")

    strategies = list(production_lines.keys())

    # 创建对比表格
    impact_data = []

    for strategy in strategies:
        production_line = production_lines[strategy]

        # 统计受影响的订单
        orders_affected = 0
        total_tardiness_increase = 0
        max_tardiness_increase = 0

        # 计算每个订单的延迟
```

```
        order_tardiness = {}
        for order in production_line.completed_orders:
            order_id = order['original_order_id']
            if order_id != '11':  # 排除紧急订单本身
                order_tardiness[order_id] = order['tardiness']

        # 这里需要基线数据来比较，暂时使用所有策略的平均值作为参考
        avg_tardiness_by_order = {}
        for order_id in set(
                [o['original_order_id'] for o in
production_line.completed_orders if o['original_order_id'] !=
'11']):
            tardiness_values = []
            for s in strategies:
                pl = production_lines[s]
                for order in pl.completed_orders:
                    if order['original_order_id'] == order_id:
                        tardiness_values.append(order['tardiness'])
                        break
            if tardiness_values:
                avg_tardiness_by_order[order_id] =
np.mean(tardiness_values)

        # 计算影响
        for order_id, tardiness in order_tardiness.items():
            if order_id in avg_tardiness_by_order:
                increase = tardiness -
avg_tardiness_by_order[order_id]
                if increase > 0:
                    orders_affected += 1
                    total_tardiness_increase += increase
                    max_tardiness_increase =
max(max_tardiness_increase, increase)

        avg_tardiness_increase = total_tardiness_increase /
max(orders_affected, 1)

        impact_data.append({
            'strategy': strategy,
            'orders_affected': orders_affected,
            'avg_tardiness_increase': avg_tardiness_increase,
            'max_tardiness_increase': max_tardiness_increase
        })
```

```
        print(f"\n策略 {strategy}:")
        print(f"  受影响的订单数量: {orders_affected}")
        print(f"  平均延迟增加: {avg_tardiness_increase:.1f}秒")
        print(f"  最大延迟增加: {max_tardiness_increase:.1f}秒")

    return impact_data


# 更新主函数以包含场景B
def main():
    """主函数"""
    print("开始仿真分析...")

    # 问题一：场景A基线模型
    print("\n执行问题一：场景A基线模型...")
    results_a, production_line_a = run_scenario_a()

    #场景A生成仿真视频
    print("为场景A生成仿真视频...")
    create_simulation_video(production_line_a,
"scenario_a_simulation", duration_minutes=2.5)

    # 绘制场景A结果
    print("绘制场景A分析图表...")
    plot_scenario_a_results(production_line_a)

    # 问题二：场景B插单扰动分析
    print("\n执行问题二：场景B插单扰动分析...")
    strategy_results_b, production_lines_b = run_scenario_b()

    # 绘制场景B对比结果
    print("绘制场景B调度策略对比...")
    strategy_scores =
plot_scenario_b_comparison(strategy_results_b, production_lines_b)

    # 分析紧急订单影响
    impact_data =
analyze_emergency_order_impact(production_lines_b)

    # 为最佳策略生成视频
    best_strategy = max(strategy_scores, key=strategy_scores.get)
    print(f"\n最佳调度策略: {best_strategy} (得分:
{strategy_scores[best_strategy]:.1f})")
    print(f"为最佳策略生成仿真视频...")
```

```
    create_simulation_video(production_lines_b[best_strategy],

f"scenario_b_best_strategy_{best_strategy}",
                            duration_minutes=2.5)

    print("\n 仿真分析完成!")
    print("生成的文件:")
    print("  - output/scenario_a_results.png (场景 A 分析结果)")
    print("  - output/scenario_a_simulation.mp4 (场景 A 仿真视频)")
    print("  - output/scenario_b_comparison.png (场景 B 调度策略对比)")
    print(f"  - output/scenario_b_best_strategy_{best_strategy}.mp4
(场景 B 最佳策略仿真视频)")

    # 输出场景 B 总结
    print("\n=== 场景 B 总结 ===")
    print("不同调度策略在紧急插单情况下的表现:")
    for strategy in strategy_results_b.keys():
        results = strategy_results_b[strategy]
        emergency_on_time = any(order['original_order_id'] == '11'
and order['is_on_time']
                                for order in
production_lines_b[strategy].completed_orders)

        print(f"\n{strategy}:")
        print(f"  紧急订单准时: {'是' if emergency_on_time else '否'}")
        print(f"  总体准交率:
{results['on_time_delivery_rate']:.1f}%")
        print(f"  平均延迟: {results['average_tardiness']:.1f}秒")
        print(f"  综合评分: {strategy_scores[strategy]:.1f}")

if __name__ == "__main__":
    main()
```

10.1.7 可落地优化方案（Python）

```
import simpy
import numpy as np
import pandas as pd
import matplotlib.pyplot as plt
import seaborn as sns
from collections import defaultdict, deque
```

```
import random
from datetime import datetime
import matplotlib
import matplotlib.animation as animation
from matplotlib.patches import Rectangle, Circle, FancyBboxPatch
import os
import warnings

warnings.filterwarnings('ignore')
# 更可靠的中文字体设置
plt.rcParams['font.sans-serif'] = ['SimHei', 'DejaVu Sans']  # 设置
中文字体
plt.rcParams['axes.unicode_minus'] = False  # 解决负号显示问题
matplotlib.rcParams['font.sans-serif'] = ['SimHei', 'DejaVu Sans']
matplotlib.rcParams['axes.unicode_minus'] = False

# 创建输出目录
if not os.path.exists('output'):
    os.makedirs('output')


class RemoteControlProductionLine:
    def __init__(self, env, layout_type='straight',
scheduling_strategy='FIFO',
                 optimization_strategy=None,
wip_cap_adjustments=None):
        self.env = env
        self.layout_type = layout_type
        self.scheduling_strategy = scheduling_strategy
        self.optimization_strategy = optimization_strategy
        self.wip_cap_adjustments = wip_cap_adjustments or {}

        # 工序参数表
        self.processes = [
            {'name': '主板拆放', 'time': 7.0, 'workers': 2,
'distance': 1, 'type': 'pre-assembly'},
            {'name': '上壳安装', 'time': 10.2, 'workers': 2,
'distance': 1, 'type': 'pre-assembly'},
            {'name': '放按键壳', 'time': 3.6, 'workers': 1,
'distance': 1, 'type': 'pre-assembly'},
            {'name': '装 PCB 上下壳', 'time': 10.4, 'workers': 4,
'distance': 2, 'type': 'assembly'},
            {'name': '尾部钉钉', 'time': 7.4, 'workers': 2,
'distance': 1, 'type': 'assembly'},
```

```
            {'name': '装小面盖', 'time': 6.7, 'workers': 2,
'distance': 1, 'type': 'assembly'},
            {'name': '电性能测试', 'time': 32.8, 'workers': 8,
'distance': 5, 'type': 'testing'},
            {'name': '单键测试', 'time': 9.8, 'workers': 3,
'distance': 2, 'type': 'testing'},
            {'name': '装入电池盖', 'time': 4.7, 'workers': 2,
'distance': 1, 'type': 'testing'},
            {'name': '外观检', 'time': 15.3, 'workers': 3, 'distance':
2, 'type': 'testing'},
            {'name': '包装遥控器', 'time': 4.2, 'workers': 1,
'distance': 2, 'type': 'packaging'},
            {'name': '封 PE', 'time': 3.1, 'workers': 1, 'distance':
2, 'type': 'packaging'},
            {'name': '封热电池', 'time': 6.6, 'workers': 1,
'distance': 2, 'type': 'packaging'},
            {'name': '遥控器装箱', 'time': 3.1, 'workers': 1,
'distance': 2, 'type': 'packaging'}
        ]

        # 应用优化策略
        self.apply_optimizations()

        # 资源配置
        self.total_workers = 33
        self.worker_pool = simpy.Resource(env,
capacity=self.total_workers)

        # 设备资源
        self.test_computers = simpy.Resource(env, capacity=8)
        self.screw_machines = simpy.Resource(env, capacity=2)
        self.heat_sealers = simpy.Resource(env, capacity=1)

        # 在制品限制和队列
        self.wip_limits = {i: self.wip_cap_adjustments.get(i, 15)
for i in range(len(self.processes))}
        self.process_queues = {i: deque() for i in
range(len(self.processes))}

        # 维护状态
        self.maintenance_active = False
        self.maintenance_process = 11  # 封 PE 工序

        # 统计信息
```

```
        self.order_stats = []
        self.process_stats = {i: {
            'queue_lengths': [],
            'processing_times': [],
            'waiting_times': [],
            'utilization': 0,
            'busy_time': 0,
            'idle_time': 0,
            'total_time': 0
        } for i in range(len(self.processes))}

        # 资源利用统计
        self.resource_stats = {
            'workers': {'busy_time': 0, 'total_capacity':
self.total_workers * 6000},
            'test_computers': {'busy_time': 0, 'total_capacity': 8 *
6000},
            'screw_machines': {'busy_time': 0, 'total_capacity': 2 *
6000},
            'heat_sealers': {'busy_time': 0, 'total_capacity': 1 *
6000}
        }

        self.wip_levels = []
        self.resource_utilization = {
            'workers': [],
            'test_computers': [],
            'screw_machines': [],
            'heat_sealers': []
        }

        # 订单管理
        self.pending_orders = []
        self.completed_orders = []
        self.current_wip = 0

        # 时间跟踪
        self.last_stat_time = 0
        self.simulation_start = 0

        # 甘特图数据
        self.gantt_data = []

        # 视频记录数据
```

```
        self.video_data = {
            'time_points': [],
            'wip_values': [],
            'queue_lengths': [],
            'completed_orders': [],
            'active_orders': [],
            'resource_utilization': []
        }

    def apply_optimizations(self):
        """应用优化策略"""
        if self.optimization_strategy == 'u_line_bottleneck':
            # U型线瓶颈优化：针对电性能测试和外观检查工序
            for process in self.processes:
                if process['name'] == '电性能测试':
                    process['time'] = 28.0  # 优化测试流程
                    process['workers'] = 6  # U型线可以共享工人，减少专用工
人
                elif process['name'] == '外观检':
                    process['time'] = 12.0  # 优化检查流程
                    process['workers'] = 2  # U型线减少专职检查员
                elif process['name'] == '单键测试':
                    process['time'] = 8.5  # 优化测试流程
                # U型线减少移动距离
                process['distance'] = max(0.5, process['distance'] *
0.6)  # 减少40%移动距离

        elif self.optimization_strategy == 'u_line_balanced':
            # U型线平衡优化
            for process in self.processes:
                if process['name'] == '电性能测试':
                    process['time'] = 26.0  # 进一步优化
                    process['workers'] = 5  # U型线多能工
                elif process['name'] == '外观检':
                    process['time'] = 10.0
                    process['workers'] = 2
                elif process['name'] == '单键测试':
                    process['time'] = 7.5
                    process['workers'] = 2
                elif process['name'] == '装PCB上下壳':
                    process['time'] = 9.0  # 优化组装流程
                    process['workers'] = 3  # U型线减少工人
                # U型线进一步减少移动距离
                process['distance'] = max(0.3, process['distance'] *
```

```
0.4)  # 减少60%移动距离

        elif self.optimization_strategy == 'u_line_comprehensive':
            # U型线综合优化
            for process in self.processes:
                if process['name'] == '电性能测试':
                    process['time'] = 24.0  # 显著优化
                    process['workers'] = 4  # U型线高度共享工人
                elif process['name'] == '外观检':
                    process['time'] = 8.0
                    process['workers'] = 1  # 多能工兼任
                elif process['name'] == '单键测试':
                    process['time'] = 6.5
                    process['workers'] = 1
                elif process['name'] == '装PCB上下壳':
                    process['time'] = 8.0
                    process['workers'] = 2
                elif process['name'] == '上壳安装':
                    process['time'] = 8.5
                elif process['name'] == '尾部钉钉':
                    process['time'] = 6.0
                # U型线最小化移动距离
                process['distance'] = max(0.2, process['distance'] *
0.3)  # 减少70%移动距离

    def calculate_priority(self, order, current_time):
        """计算订单优先级"""
        if self.scheduling_strategy == 'EDD':
            return -order['due_time']  # 最早交期优先
        elif self.scheduling_strategy == 'Slack':
            remaining_time = order['due_time'] - current_time
            remaining_work = sum(p['time'] for p in self.processes)
            slack = remaining_time - remaining_work
            return -slack  # 最小松弛时间优先
        elif self.scheduling_strategy == 'CR':
            remaining_time = order['due_time'] - current_time
            remaining_work = sum(p['time'] for p in self.processes)
            return remaining_time / max(remaining_work, 1)  # 关键比率
最小优先
        elif self.scheduling_strategy == 'PR+CR':
            priority_weights = {'低': 1.0, '中': 1.5, '高': 2.0, '最高
': 3.0}
            weight = priority_weights.get(order['priority'], 1.0)
            remaining_time = order['due_time'] - current_time
```

```
            remaining_work = sum(p['time'] for p in self.processes)
            cr = remaining_time / max(remaining_work, 1)
            return weight * (1 / max(cr, 0.1))  # 组合优先级
        else:  # FIFO
            return current_time - order['arrival_time']  # 先进先出

    def select_next_order(self, process_id):
        """选择下一个要处理的订单"""
        if not self.process_queues[process_id]:
            return None

        current_time = self.env.now
        orders_with_priority = []

        for order in list(self.process_queues[process_id]):
            priority = self.calculate_priority(order, current_time)
            orders_with_priority.append((priority, order))

        # 根据优先级排序（数值越大优先级越高）
        orders_with_priority.sort(key=lambda x: x[0], reverse=True)
        return orders_with_priority[0][1] if orders_with_priority
else None

    def process_station(self, process_id):
        """处理工作站"""
        while True:
            # 检查WIP上限
            if len(self.process_queues[process_id]) >=
self.wip_limits[process_id]:
                self.process_stats[process_id]['idle_time'] += 1
                yield self.env.timeout(1)
                continue

            # 选择下一个订单
            next_order = self.select_next_order(process_id)
            if next_order is None:
                self.process_stats[process_id]['idle_time'] += 1
                yield self.env.timeout(1)
                continue

            process = self.processes[process_id]
            self.process_queues[process_id].remove(next_order)

            # 记录等待时间
```

```
            wait_time = self.env.now -
next_order[f'process_{process_id}_start']

self.process_stats[process_id]['waiting_times'].append(wait_time)

            # 检查是否处于维护期间
            if process_id == self.maintenance_process and
self.maintenance_active:
                while self.maintenance_active:
                    self.process_stats[process_id]['idle_time'] += 1
                    yield self.env.timeout(1)

            # 请求工人资源
            workers_needed = process['workers']
            with self.worker_pool.request() as req:
                yield req
                start_time = self.env.now

                # 记录甘特图开始
                gantt_start = self.env.now

                # 特殊设备请求
                equipment_resource = None
                resource_type = None
                equipment_capacity = 1

                if process['name'] == '电性能测试':
                    equipment_resource = self.test_computers
                    resource_type = 'test_computers'
                    equipment_capacity = 8
                elif process['name'] == '尾部钉钉':
                    equipment_resource = self.screw_machines
                    resource_type = 'screw_machines'
                    equipment_capacity = 2
                elif process['name'] in ['封 PE', '封热电池']:
                    equipment_resource = self.heat_sealers
                    resource_type = 'heat_sealers'
                    equipment_capacity = 1

                if equipment_resource:
                    with equipment_resource.request() as equip_req:
                        yield equip_req
                        actual_time = process['time'] *
random.uniform(0.9, 1.1)
```

```
                    # 记录设备忙碌时间
                    self.resource_stats[resource_type]['busy_time']
+= actual_time * equipment_capacity
                    # 记录工人忙碌时间
                    self.resource_stats['workers']['busy_time'] +=
actual_time * workers_needed
                    # 记录工序忙碌时间
                    self.process_stats[process_id]['busy_time'] +=
actual_time

                    yield self.env.timeout(actual_time)
                else:
                    actual_time = process['time'] *
random.uniform(0.9, 1.1)
                    # 记录工人忙碌时间
                    self.resource_stats['workers']['busy_time'] +=
actual_time * workers_needed
                    # 记录工序忙碌时间
                    self.process_stats[process_id]['busy_time'] +=
actual_time
                    yield self.env.timeout(actual_time)

                end_time = self.env.now

                # 记录甘特图
                self.gantt_data.append({
                    'order_id': next_order['id'],
                    'process_id': process_id,
                    'process_name': process['name'],
                    'start_time': gantt_start,
                    'end_time': end_time,
                    'duration': actual_time
                })


self.process_stats[process_id]['processing_times'].append(actual_ti
me)

                # 更新订单状态
                next_order['current_process'] = process_id + 1
                if process_id == len(self.processes) - 1:
                    # 订单完成
                    next_order['completion_time'] = end_time
```

```
                next_order['flow_time'] = end_time -
next_order['arrival_time']
                next_order['tardiness'] = max(0, end_time -
next_order['due_time'])
                next_order['is_on_time'] = end_time <=
next_order['due_time']
                self.completed_orders.append(next_order)
                self.current_wip -= 1

                self.order_stats.append({
                    'order_id': next_order['id'],
                    'arrival_time': next_order['arrival_time'],
                    'completion_time': end_time,
                    'flow_time': next_order['flow_time'],
                    'tardiness': next_order['tardiness'],
                    'is_on_time': next_order['is_on_time'],
                    'quantity': next_order['quantity'],
                    'priority': next_order['priority']
                })
            else:
                # 进入下一工序队列
                next_order[f'process_{process_id + 1}_start'] =
self.env.now
                self.process_queues[process_id +
1].append(next_order)

            # 更新队列统计
            self.update_statistics()

    def update_statistics(self):
        """更新统计信息"""
        current_time = self.env.now
        time_interval = current_time - self.last_stat_time

        if time_interval >= 10:
            self.wip_levels.append({
                'time': current_time,
                'wip': self.current_wip
            })

            for process_id in range(len(self.processes)):
                queue_length = len(self.process_queues[process_id])

self.process_stats[process_id]['queue_lengths'].append({
```

```
                    'time': current_time,
                    'length': queue_length
                })

            self.video_data['time_points'].append(current_time)
            self.video_data['wip_values'].append(self.current_wip)

self.video_data['completed_orders'].append(len(self.completed_order
s))

self.video_data['active_orders'].append(len(self.pending_orders) -
len(self.completed_orders))

            queue_lengths = []
            for i in range(len(self.processes)):
                queue_lengths.append(len(self.process_queues[i]))
            self.video_data['queue_lengths'].append(queue_lengths)

            resource_util = {}
            total_time = current_time - self.simulation_start
            if total_time > 0:
                worker_util =
(self.resource_stats['workers']['busy_time'] /

self.resource_stats['workers']['total_capacity']) * 100
                test_computer_util =
(self.resource_stats['test_computers']['busy_time'] /

self.resource_stats['test_computers']['total_capacity']) * 100
                screw_machine_util =
(self.resource_stats['screw_machines']['busy_time'] /

self.resource_stats['screw_machines']['total_capacity']) * 100
                heat_sealer_util =
(self.resource_stats['heat_sealers']['busy_time'] /

self.resource_stats['heat_sealers']['total_capacity']) * 100

                resource_util = {
                    'workers': min(100, worker_util),
                    'test_computers': min(100, test_computer_util),
                    'screw_machines': min(100, screw_machine_util),
                    'heat_sealers': min(100, heat_sealer_util)
                }
```

```
            else:
                resource_util = {
                    'workers': 0,
                    'test_computers': 0,
                    'screw_machines': 0,
                    'heat_sealers': 0
                }


self.video_data['resource_utilization'].append(resource_util)
            self.last_stat_time = current_time

    def order_generator(self):
        """订单生成器"""
        all_orders = [
            {'id': '01', 'product': '遥控器A', 'quantity': 28,
'arrival_time': 0, 'due_time': 4022, 'priority': '中'},
            {'id': '02', 'product': '遥控器B', 'quantity': 16,
'arrival_time': 300, 'due_time': 2297, 'priority': '中'},
            {'id': '03', 'product': '遥控器C', 'quantity': 35,
'arrival_time': 0, 'due_time': 5027, 'priority': '中'},
            {'id': '04', 'product': '遥控器D', 'quantity': 22,
'arrival_time': 600, 'due_time': 3160, 'priority': '中'},
            {'id': '05', 'product': '遥控器E', 'quantity': 19,
'arrival_time': 900, 'due_time': 2729, 'priority': '中'},
            {'id': '06', 'product': '遥控器F', 'quantity': 32,
'arrival_time': 1200, 'due_time': 4597,
             'priority': '中'},
            {'id': '07', 'product': '遥控器G', 'quantity': 25,
'arrival_time': 1500, 'due_time': 3591,
             'priority': '高'},
            {'id': '08', 'product': '遥控器H', 'quantity': 13,
'arrival_time': 1800, 'due_time': 1868,
             'priority': '低'},
            {'id': '09', 'product': '遥控器I', 'quantity': 31,
'arrival_time': 2100, 'due_time': 4452,
             'priority': '中'},
            {'id': '010', 'product': '遥控器J', 'quantity': 20,
'arrival_time': 2400, 'due_time': 2873,
             'priority': '中'},
            {'id': '011', 'product': '遥控器R', 'quantity': 12,
'arrival_time': 1800, 'due_time': 2400,
             'priority': '最高'}
        ]
```

```
        all_orders.sort(key=lambda x: x['arrival_time'])

        for order_info in all_orders:
            if order_info['arrival_time'] > self.env.now:
                yield self.env.timeout(order_info['arrival_time'] -
self.env.now)

            print(f"订单 {order_info['id']} 在时间 {self.env.now} 到达,
数量: {order_info['quantity']}")

            for product_index in range(order_info['quantity']):
                product = order_info.copy()
                product['id'] = f"{order_info['id']}-{product_index +
1:03d}"
                product['arrival_time'] = self.env.now
                product['current_process'] = 0
                product['process_0_start'] = self.env.now
                product['completion_time'] = None
                product['flow_time'] = None
                product['tardiness'] = None
                product['is_on_time'] = None
                product['original_order_id'] = order_info['id']
                product['quantity'] = 1

                self.process_queues[0].append(product)
                self.current_wip += 1
                self.pending_orders.append(product)

                if product_index < order_info['quantity'] - 1:
                    yield self.env.timeout(3.5)

    def maintenance_event(self):
        """计划性维护事件"""
        yield self.env.timeout(2700)
        print(f"维护开始于: {self.env.now}")
        self.maintenance_active = True
        yield self.env.timeout(150)
        self.maintenance_active = False
        print(f"维护结束于: {self.env.now}")

    def run_simulation(self, simulation_time=6000):
        """运行仿真"""
        self.simulation_start = self.env.now
```

```
        for i in range(len(self.processes)):
            self.env.process(self.process_station(i))

        self.env.process(self.order_generator())
        self.env.process(self.maintenance_event())
        self.last_stat_time = 0
        self.env.process(self.update_statistics_continuous())

        print(f"开始仿真，总时长: {simulation_time} 秒")
        self.env.run(until=simulation_time)

        return self.analyze_results()

    def update_statistics_continuous(self):
        """持续更新统计信息"""
        while True:
            self.update_statistics()
            yield self.env.timeout(10)

    def analyze_results(self):
        """分析仿真结果"""
        if not self.order_stats:
            return {
                'total_orders': 0, 'completed_orders': 0,
'on_time_delivery_rate': 0,
                'average_flow_time': 0, 'average_tardiness': 0,
'max_tardiness': 0,
                'throughput': 0, 'avg_wip': 0, 'bottleneck_process':
None
            }

        df_orders = pd.DataFrame(self.order_stats)

        simulation_hours = 6000 / 3600
        throughput = len(df_orders) / simulation_hours
        avg_wip = np.mean([w['wip'] for w in self.wip_levels]) if
self.wip_levels else 0
        bottleneck_process = self.identify_bottleneck()

        # 计算资源利用率
        worker_util = (self.resource_stats['workers']['busy_time'] /

self.resource_stats['workers']['total_capacity']) * 100
```

```
        test_computer_util =
(self.resource_stats['test_computers']['busy_time'] /

self.resource_stats['test_computers']['total_capacity']) * 100
        screw_machine_util =
(self.resource_stats['screw_machines']['busy_time'] /

self.resource_stats['screw_machines']['total_capacity']) * 100
        heat_sealer_util =
(self.resource_stats['heat_sealers']['busy_time'] /

self.resource_stats['heat_sealers']['total_capacity']) * 100

        resource_utilization = {
            'workers': min(100, worker_util),
            'test_computers': min(100, test_computer_util),
            'screw_machines': min(100, screw_machine_util),
            'heat_sealers': min(100, heat_sealer_util)
        }

        # 计算总移动距离减少
        total_distance_reduction = 0
        original_distances = [1, 1, 1, 2, 1, 1, 5, 2, 1, 2, 2, 2, 2,
2]
        current_distances = [p['distance'] for p in self.processes]
        for orig, curr in zip(original_distances,
current_distances):
            total_distance_reduction += (orig - curr)

        # 计算工人效率提升
        original_workers = [2, 2, 1, 4, 2, 2, 8, 3, 2, 3, 1, 1, 1,
1]
        current_workers = [p['workers'] for p in self.processes]
        worker_reduction = sum(original_workers) -
sum(current_workers)

        results = {
            'total_orders': len(self.pending_orders) +
len(self.completed_orders),
            'completed_orders': len(df_orders),
            'on_time_delivery_rate': df_orders['is_on_time'].mean() *
100,
            'average_flow_time': df_orders['flow_time'].mean(),
            'average_tardiness': df_orders['tardiness'].mean(),
```

```
            'max_tardiness': df_orders['tardiness'].max(),
            'throughput': throughput,
            'avg_wip': avg_wip,
            'bottleneck_process': bottleneck_process,
            'scheduling_strategy': self.scheduling_strategy,
            'optimization_strategy': self.optimization_strategy,
            'resource_utilization': resource_utilization,
            'total_distance_reduction': total_distance_reduction,
            'worker_reduction': worker_reduction,
            'total_processing_time_reduction': sum(
                [7.0, 10.2, 3.6, 10.4, 7.4, 6.7, 32.8, 9.8, 4.7,
15.3, 4.2, 3.1, 6.6, 3.1]) -
                                              sum([p['time'] for p in
self.processes])
        }

        return results

    def identify_bottleneck(self):
        """识别瓶颈工序"""
        if not any(self.process_stats[i]['queue_lengths'] for i in
range(len(self.processes))):
            return None

        avg_queues = []
        for i in range(len(self.processes)):
            queues = self.process_stats[i]['queue_lengths']
            if queues:
                avg_queue = np.mean([q['length'] for q in queues])
                avg_queues.append((i, avg_queue))
            else:
                avg_queues.append((i, 0))

        avg_queues.sort(key=lambda x: x[1], reverse=True)
        bottleneck_id = avg_queues[0][0]

        total_time = 6000
        utilization =
(self.process_stats[bottleneck_id]['busy_time'] / total_time) * 100

        return {
            'process_id': bottleneck_id,
            'process_name': self.processes[bottleneck_id]['name'],
            'avg_queue_length': avg_queues[0][1],
```

```
            'avg_processing_time':
np.mean(self.process_stats[bottleneck_id]['processing_times'])
            if self.process_stats[bottleneck_id]['processing_times']
else 0,
            'utilization': utilization
        }


def generate_u_line_layout():
    """生成U型生产线布局图"""
    fig, ax = plt.subplots(figsize=(14, 10))

    # U型布局参数
    u_width = 8
    u_height = 6
    center_x = 5
    center_y = 3

    # 定义U型路径
    theta = np.linspace(np.pi, 2 * np.pi, 100)
    x_outer = center_x + (u_width / 2) * np.cos(theta)
    y_outer = center_y + (u_height / 2) * np.sin(theta)

    x_inner = center_x + (u_width / 2 - 1) * np.cos(theta)
    y_inner = center_y + (u_height / 2 - 1) * np.sin(theta)

    # 绘制U型路径
    ax.plot(x_outer, y_outer, 'k-', linewidth=2, alpha=0.7)
    ax.plot(x_inner, y_inner, 'k-', linewidth=2, alpha=0.7)

    # 添加入口和出口
    ax.plot([center_x - u_width / 2, center_x - u_width / 2],
            [center_y - u_height / 2 + 0.5, center_y - u_height / 2],
'k-', linewidth=3)
    ax.plot([center_x + u_width / 2, center_x + u_width / 2],
            [center_y - u_height / 2 + 0.5, center_y - u_height / 2],
'k-', linewidth=3)

    # 工序位置（在U型线上均匀分布）
    processes = ['主板拆放', '上壳安装', '放按键壳', '装PCB上下壳', '尾
部钉钉',
                 '装小面盖', '电性能测试', '单键测试', '装入电池盖', '外观检
',
                 '包装遥控器', '封PE', '封热电池', '遥控器装箱']
```

```
    process_angles = np.linspace(np.pi, 2 * np.pi, len(processes) +
1)[:-1]

    # 绘制工序点
    for i, (process, angle) in enumerate(zip(processes,
process_angles)):
        # 在内外圆之间放置工序
        r = u_width / 2 - 0.5
        x = center_x + r * np.cos(angle)
        y = center_y + (u_height / 2 - 0.5) * np.sin(angle)

        # 根据工序类型设置颜色
        if i < 6:
            color = 'lightblue'  # 预组装
        elif i < 10:
            color = 'lightcoral'  # 测试
        else:
            color = 'lightgreen'  # 包装

        # 绘制工序节点
        circle = plt.Circle((x, y), 0.3, color=color, ec='black',
zorder=5)
        ax.add_patch(circle)

        # 添加工序标签
        ax.text(x, y + 0.4, process, ha='center', va='bottom',
                fontsize=7, rotation=angle * 180 / np.pi - 90)
        ax.text(x, y - 0.4, f'工序{i + 1}', ha='center', va='top',
                fontsize=6, rotation=angle * 180 / np.pi - 90)

    # 添加工序流箭头
    for i in range(len(process_angles) - 1):
        r = u_width / 2 - 0.5
        x1 = center_x + r * np.cos(process_angles[i])
        y1 = center_y + (u_height / 2 - 0.5) *
np.sin(process_angles[i])
        x2 = center_x + r * np.cos(process_angles[i + 1])
        y2 = center_y + (u_height / 2 - 0.5) *
np.sin(process_angles[i + 1])

        ax.annotate('', xy=(x2, y2), xytext=(x1, y1),
                    arrowprops=dict(arrowstyle='->', lw=1.5,
color='red', alpha=0.7))
```

```
    # 添加物料和人员区域标注
    ax.text(center_x, center_y, '物料区\n多能工\n工作区',
            ha='center', va='center', fontsize=10,
            bbox=dict(boxstyle="round,pad=0.3",
facecolor="lightyellow", alpha=0.7))

    # 添加资源标注
    ax.text(0.5, 0.95, 'U 型生产线布局 - 遥控器组装线', fontsize=16,
            fontweight='bold', ha='center', transform=ax.transAxes)
    ax.text(0.5, 0.90, 'U 型布局 | 14 个工序 | 多能工协作 | 减少移动距离',
fontsize=10,
            ha='center', transform=ax.transAxes)

    # 添加图例
    colors = ['lightblue', 'lightcoral', 'lightgreen']
    labels = ['预组装工序', '测试工序', '包装工序']
    patches = [plt.Rectangle((0, 0), 1, 1, fc=color) for color in
colors]
    ax.legend(patches, labels, loc='upper right',
bbox_to_anchor=(0.98, 0.98))

    ax.set_xlim(center_x - u_width / 2 - 1, center_x + u_width / 2
+ 1)
    ax.set_ylim(center_y - u_height / 2 - 1, center_y + u_height /
2 + 1)
    ax.set_aspect('equal')
    ax.axis('off')

    plt.tight_layout()
    plt.savefig('output/u_line_layout.png', dpi=300,
bbox_inches='tight')
    plt.show()


def run_u_line_optimization_scenarios():
    """运行 U 型流水线优化场景比较"""
    print("=== 问题三：U 型流水线优化方案 ===")

    # 基准场景（直线布局）
    print("\n--- 基准场景（直线布局） ---")
    env = simpy.Environment()
    baseline = RemoteControlProductionLine(env,
scheduling_strategy='FIFO')
```

```
    baseline_results = baseline.run_simulation()

    print(f"基准场景结果:")
    print(f"完成订单: {baseline_results['completed_orders']}")
    print(f"准交率:
{baseline_results['on_time_delivery_rate']:.1f}%")
    print(f"吞吐量: {baseline_results['throughput']:.1f}件/小时")
    print(f"平均流动时间: {baseline_results['average_flow_time']:.1f}
秒")

    if baseline_results['bottleneck_process']:
        bottleneck = baseline_results['bottleneck_process']
        print(f"瓶颈工序: {bottleneck['process_name']} (利用率:
{bottleneck['utilization']:.1f}%)")

    # 优化场景 1：U 型线瓶颈优化
    print("\n--- 优化场景 1：U 型线瓶颈优化 ---")
    env = simpy.Environment()
    optimized1 = RemoteControlProductionLine(env,
scheduling_strategy='PR+CR',

optimization_strategy='u_line_bottleneck')
    optimized1_results = optimized1.run_simulation()

    print(f"U 型线瓶颈优化结果:")
    print(f"完成订单: {optimized1_results['completed_orders']}")
    print(f"准交率:
{optimized1_results['on_time_delivery_rate']:.1f}%")
    print(f"吞吐量: {optimized1_results['throughput']:.1f}件/小时")
    print(f"平均流动时间:
{optimized1_results['average_flow_time']:.1f}秒")
    print(f"移动距离减少:
{optimized1_results['total_distance_reduction']:.1f}米")
    print(f"工人减少: {optimized1_results['worker_reduction']}人")

    # 优化场景 2：U 型线平衡优化
    print("\n--- 优化场景 2：U 型线平衡优化 ---")
    env = simpy.Environment()
    optimized2 = RemoteControlProductionLine(env,
scheduling_strategy='PR+CR',

optimization_strategy='u_line_balanced')
    optimized2_results = optimized2.run_simulation()
```

```
    print(f"U 型线平衡优化结果:")
    print(f"完成订单: {optimized2_results['completed_orders']}")
    print(f"准交率:
{optimized2_results['on_time_delivery_rate']:.1f}%")
    print(f"吞吐量: {optimized2_results['throughput']:.1f}件/小时")
    print(f"平均流动时间:
{optimized2_results['average_flow_time']:.1f}秒")
    print(f"移动距离减少:
{optimized2_results['total_distance_reduction']:.1f}米")
    print(f"工人减少: {optimized2_results['worker_reduction']}人")

    # 优化场景 3：U 型线综合优化
    print("\n--- 优化场景 3：U 型线综合优化 ---")
    env = simpy.Environment()
    optimized3 = RemoteControlProductionLine(env,
scheduling_strategy='PR+CR',

optimization_strategy='u_line_comprehensive')
    optimized3_results = optimized3.run_simulation()

    print(f"U 型线综合优化结果:")
    print(f"完成订单: {optimized3_results['completed_orders']}")
    print(f"准交率:
{optimized3_results['on_time_delivery_rate']:.1f}%")
    print(f"吞吐量: {optimized3_results['throughput']:.1f}件/小时")
    print(f"平均流动时间:
{optimized3_results['average_flow_time']:.1f}秒")
    print(f"移动距离减少:
{optimized3_results['total_distance_reduction']:.1f}米")
    print(f"工人减少: {optimized3_results['worker_reduction']}人")
    print(f"总加工时间减少:
{optimized3_results['total_processing_time_reduction']:.1f}秒")

    return {
        'baseline': baseline_results,
        'u_line_bottleneck': optimized1_results,
        'u_line_balanced': optimized2_results,
        'u_line_comprehensive': optimized3_results
    }, [baseline, optimized1, optimized2, optimized3]


def plot_u_line_optimization_comparison(results_dict):
    """绘制 U 型线优化方案比较图"""
    scenarios = ['基准场景', 'U 型瓶颈优化', 'U 型平衡优化', 'U 型综合优化
```

```
']
    scenario_keys = ['baseline', 'u_line_bottleneck',
'u_line_balanced', 'u_line_comprehensive']

    # 主要性能指标
    fig, axes = plt.subplots(2, 3, figsize=(18, 12))
    axes = axes.flatten()

    metrics = ['on_time_delivery_rate', 'throughput',
'average_flow_time',
               'avg_wip', 'total_distance_reduction',
'worker_reduction']
    titles = ['准交率 (%)', '吞吐量 (件/小时)', '平均流动时间 (秒)',
              '平均在制品 (件)', '移动距离减少 (米)', '工人减少 (人)']

    colors = ['lightcoral', 'lightgreen', 'lightblue', 'gold']

    for i, (metric, title) in enumerate(zip(metrics, titles)):
        values = [results_dict[key][metric] for key in
scenario_keys]
        bars = axes[i].bar(scenarios, values, color=colors)
        axes[i].set_title(f'{title}', fontsize=12,
fontweight='bold')
        axes[i].set_ylabel(title)
        axes[i].grid(True, alpha=0.3)
        axes[i].tick_params(axis='x', rotation=15)

        # 在柱状图上添加数值
        for bar, value in zip(bars, values):
            height = bar.get_height()
            axes[i].text(bar.get_x() + bar.get_width() / 2., height +
max(values) * 0.01,
                         f'{value:.1f}', ha='center', va='bottom',
fontweight='bold')

    plt.tight_layout()
    plt.savefig('output/u_line_optimization_comparison.png',
dpi=300, bbox_inches='tight')
    plt.show()


def create_u_line_optimization_report(results_dict):
    """生成U型线优化分析报告"""
    print("\n" + "=" * 80)
```

```
    print("                U 型流水线优化方案分析报告")
    print("=" * 80)

    baseline = results_dict['baseline']
    bottleneck_opt = results_dict['u_line_bottleneck']
    balanced_opt = results_dict['u_line_balanced']
    comprehensive_opt = results_dict['u_line_comprehensive']

    print(f"\n基准场景性能 (直线布局):")
    print(f"  • 完成订单数: {baseline['completed_orders']}")
    print(f"  • 准交率: {baseline['on_time_delivery_rate']:.1f}%")
    print(f"  • 吞吐量: {baseline['throughput']:.1f}件/小时")
    print(f"  • 平均流动时间: {baseline['average_flow_time']:.1f}秒")
    print(f"  • 平均在制品: {baseline['avg_wip']:.1f}件")

    if baseline['bottleneck_process']:
        bottleneck = baseline['bottleneck_process']
        print(f"  • 瓶颈工序: {bottleneck['process_name']} (利用率:
{bottleneck['utilization']:.1f}%)")

    print(f"\nU 型流水线优化效果对比:")

    # U 型瓶颈优化效果
    improvement1 = bottleneck_opt['on_time_delivery_rate'] -
baseline['on_time_delivery_rate']
    throughput_improvement1 = bottleneck_opt['throughput'] -
baseline['throughput']
    print(f"\n1. U 型线瓶颈优化方案:")
    print(f"   • 准交率改善: {improvement1:+.1f}%")
    print(f"   • 吞吐量改善: {throughput_improvement1:+.1f}件/小时")
    print(f"   • 流动时间减少: {baseline['average_flow_time'] -
bottleneck_opt['average_flow_time']:+.1f}秒")
    print(f"   • 移动距离减少:
{bottleneck_opt['total_distance_reduction']:.1f}米")
    print(f"   • 工人减少: {bottleneck_opt['worker_reduction']}人")
    print(f"   • 主要措施: U 型布局 + 瓶颈工序优化 + 多能工协作")

    # U 型平衡优化效果
    improvement2 = balanced_opt['on_time_delivery_rate'] -
baseline['on_time_delivery_rate']
    throughput_improvement2 = balanced_opt['throughput'] -
baseline['throughput']
    print(f"\n2. U 型线平衡优化方案:")
    print(f"   • 准交率改善: {improvement2:+.1f}%")
```

```
    print(f"   • 吞吐量改善: {throughput_improvement2:+.1f}件/小时")
    print(f"   • 流动时间减少: {baseline['average_flow_time'] -
balanced_opt['average_flow_time']:+.1f}秒")
    print(f"   • 移动距离减少:
{balanced_opt['total_distance_reduction']:.1f}米")
    print(f"   • 工人减少: {balanced_opt['worker_reduction']}人")
    print(f"   • 主要措施: U 型布局 + 产线平衡 + 流程优化")

    # U 型综合优化效果
    improvement3 = comprehensive_opt['on_time_delivery_rate'] -
baseline['on_time_delivery_rate']
    throughput_improvement3 = comprehensive_opt['throughput'] -
baseline['throughput']
    print(f"\n3. U 型线综合优化方案:")
    print(f"   • 准交率改善: {improvement3:+.1f}%")
    print(f"   • 吞吐量改善: {throughput_improvement3:+.1f}件/小时")
    print(f"   • 流动时间减少: {baseline['average_flow_time'] -
comprehensive_opt['average_flow_time']:+.1f}秒")
    print(f"   • 移动距离减少:
{comprehensive_opt['total_distance_reduction']:.1f}米")
    print(f"   • 工人减少: {comprehensive_opt['worker_reduction']}人")
    print(f"   • 总加工时间减少:
{comprehensive_opt['total_processing_time_reduction']:.1f}秒")
    print(f"   • 主要措施: U 型布局 + 综合优化 + 多能工 + 精益生产")

    # 推荐最佳方案
    best_scenario = max([(k, v['on_time_delivery_rate']) for k, v
in results_dict.items()],
                        key=lambda x: x[1])

    scenario_names = {
        'baseline': '基准场景',
        'u_line_bottleneck': 'U 型瓶颈优化',
        'u_line_balanced': 'U 型平衡优化',
        'u_line_comprehensive': 'U 型综合优化'
    }

    print(f"\n🎯 推荐最佳方案: {scenario_names[best_scenario[0]]}")
    print(
        f"   准交率: {best_scenario[1]:.1f}% (相比基准改善:
{best_scenario[1] - baseline['on_time_delivery_rate']:+.1f}%)")
    print(
        f"   预计年效益: 生产效率提升{best_scenario[1] -
baseline['on_time_delivery_rate']:.1f}%, 人工成本降低
```

```
{comprehensive_opt['worker_reduction'] / 33 * 100:.1f}%")


def check_video_writers():
    """检查可用的视频写入器"""
    print("检查可用的视频写入器...")
    available_writers = animation.writers.list()
    print(f"可用的写入器: {available_writers}")

    # 尝试获取 ffmpeg 写入器信息
    try:
        ffmpeg_writer = animation.writers['ffmpeg']
        print(f"FFmpeg 写入器可用")
        print(f"FFmpeg 信息: {ffmpeg_writer}")
    except (KeyError, RuntimeError) as e:
        print(f"FFmpeg 写入器不可用: {e}")

    # 尝试获取 pillow 写入器信息
    try:
        pillow_writer = animation.writers['pillow']
        print(f"Pillow 写入器可用")
    except (KeyError, RuntimeError) as e:
        print(f"Pillow 写入器不可用: {e}")

    return available_writers


def create_simulation_video(production_line,
video_name="simulation_video", duration_minutes=2):
    """创建仿真过程视频 - 修复编码器问题"""
    print(f"生成仿真视频: {video_name} (目标时长: {duration_minutes}分
钟)")

    # 设置中文字体
    plt.rcParams['font.sans-serif'] = ['SimHei', 'DejaVu Sans']
    plt.rcParams['axes.unicode_minus'] = False

    # 检查可用写入器
    available_writers = check_video_writers()

    # 计算需要的帧数
    fps = 10
    total_frames = int(duration_minutes * 60 * fps)
```

```
    # 数据预处理 - 确保有足够的数据点
    original_points =
len(production_line.video_data['time_points'])
    if original_points < total_frames:
        print(f"原始数据点: {original_points}, 目标帧数:
{total_frames}, 进行数据扩展...")

        # 使用最后一个有效值填充
        last_wip = production_line.video_data['wip_values'][-1] if
production_line.video_data['wip_values'] else 0
        last_completed =
production_line.video_data['completed_orders'][-1] if
production_line.video_data[
            'completed_orders'] else 0
        last_active = production_line.video_data['active_orders'][-
1] if production_line.video_data[
            'active_orders'] else 0
        last_queues = production_line.video_data['queue_lengths'][-
1] if production_line.video_data[
            'queue_lengths'] else [0] * 14
        last_util =
production_line.video_data['resource_utilization'][-1] if
production_line.video_data[
            'resource_utilization'] else {
            'workers': 0, 'test_computers': 0, 'screw_machines': 0,
'heat_sealers': 0
        }

        # 扩展数据
        for i in range(original_points, total_frames):
            production_line.video_data['time_points'].append(6000 * i
/ total_frames)
            production_line.video_data['wip_values'].append(last_wip)

production_line.video_data['completed_orders'].append(last_complete
d)

production_line.video_data['active_orders'].append(last_active)

production_line.video_data['queue_lengths'].append(last_queues.copy
())

production_line.video_data['resource_utilization'].append(last_util
.copy())
```

```
    # 创建图形和固定的子图布局
    fig = plt.figure(figsize=(20, 12), dpi=100)

    # 预定义子图位置
    ax1 = plt.subplot(3, 4, 1)  # 在制品水平
    ax2 = plt.subplot(3, 4, 2)  # 订单状态
    ax3 = plt.subplot(3, 4, 3)  # 队列长度
    ax4 = plt.subplot(3, 4, 4)  # 资源利用率
    ax5 = plt.subplot(3, 4, 5)  # 性能指标
    ax6 = plt.subplot(3, 4, 6)  # U型布局
    ax7 = plt.subplot(3, 4, 7)  # 瓶颈分析
    ax8 = plt.subplot(3, 4, 8)  # 优化效果
    ax9 = plt.subplot(3, 4, 9)  # 仿真进度

    # 设置固定的坐标轴范围
    wip_max = max(production_line.video_data['wip_values']) * 1.2
if production_line.video_data['wip_values'] else 50
    order_max = max(
        production_line.video_data['completed_orders'] +
production_line.video_data['active_orders']) * 1.2 if \
    production_line.video_data['completed_orders'] else 50

    def animate(i):
        # 清除所有子图
        for ax in [ax1, ax2, ax3, ax4, ax5, ax6, ax7, ax8, ax9]:
            ax.clear()
            # 在每个子图中重新设置字体
            ax.tick_params(labelsize=8)

        current_frame = min(i,
len(production_line.video_data['time_points']) - 1)

        times =
production_line.video_data['time_points'][:current_frame + 1]
        wips =
production_line.video_data['wip_values'][:current_frame + 1]
        completed =
production_line.video_data['completed_orders'][:current_frame + 1]
        active =
production_line.video_data['active_orders'][:current_frame + 1]

        # 1. 在制品水平 - 固定坐标轴
        ax1.plot(times, wips, 'b-', linewidth=2, alpha=0.8)
```

```
        ax1.fill_between(times, wips, alpha=0.3, color='blue')
        ax1.set_xlabel('时间 (秒)', fontsize=9)
        ax1.set_ylabel('在制品数量 (件)', fontsize=9)
        ax1.set_title('在制品水平实时变化', fontsize=11,
fontweight='bold')
        ax1.set_ylim(0, wip_max)
        ax1.set_xlim(0, 6000)
        ax1.grid(True, alpha=0.3)

        # 2. 订单状态 - 固定坐标轴
        ax2.plot(times, completed, 'g-', linewidth=2, label='完成订单
', alpha=0.8)
        ax2.plot(times, active, 'r-', linewidth=2, label='活跃订单',
alpha=0.8)
        ax2.fill_between(times, completed, alpha=0.3, color='green')
        ax2.fill_between(times, active, alpha=0.2, color='red')
        ax2.set_xlabel('时间 (秒)', fontsize=9)
        ax2.set_ylabel('订单数量', fontsize=9)
        ax2.set_title('订单状态跟踪', fontsize=11, fontweight='bold')
        ax2.set_ylim(0, order_max)
        ax2.set_xlim(0, 6000)
        ax2.legend(fontsize=8)
        ax2.grid(True, alpha=0.3)

        # 3. 各工序队列长度 - 固定坐标轴
        process_names = [p['name'] for p in
production_line.processes]
        if current_frame >= 0:
            current_queues =
production_line.video_data['queue_lengths'][current_frame]
            colors = ['lightcoral' if q > 5 else 'lightblue' for q in
current_queues]
            bars = ax3.bar(range(len(process_names)), current_queues,
color=colors, alpha=0.8)
            ax3.set_xlabel('工序', fontsize=9)
            ax3.set_ylabel('队列长度', fontsize=9)
            ax3.set_title(f'各工序队列长度 (时间: {times[-1]:.0f}秒)',
fontsize=11, fontweight='bold')
            ax3.set_xticks(range(len(process_names)))
            ax3.set_xticklabels([f'工序{i + 1}' for i in
range(len(process_names))], rotation=45, ha='right',
                                fontsize=6)
            ax3.set_ylim(0, max(current_queues) * 1.2 if
current_queues else 10)
```

```
            ax3.grid(True, alpha=0.3)

            for bar, value in zip(bars, current_queues):
                ax3.text(bar.get_x() + bar.get_width() / 2.,
bar.get_height() + 0.1,
                         f'{value}', ha='center', va='bottom',
fontsize=6)

        # 4. 资源利用率 - 固定坐标轴
        if current_frame >= 0 and
production_line.video_data['resource_utilization']:
            current_utils =
production_line.video_data['resource_utilization'][current_frame]
            resource_names = ['工人', '测试电脑', '螺丝机', '热风机']
            util_values = [
                current_utils.get('workers', 0),
                current_utils.get('test_computers', 0),
                current_utils.get('screw_machines', 0),
                current_utils.get('heat_sealers', 0)
            ]

            colors = ['gold' if u > 80 else 'lightgreen' for u in
util_values]
            bars = ax4.bar(resource_names, util_values, color=colors,
alpha=0.8)
            ax4.set_xlabel('资源类型', fontsize=9)
            ax4.set_ylabel('利用率 (%)', fontsize=9)
            ax4.set_title('资源利用率监控', fontsize=11,
fontweight='bold')
            ax4.set_ylim(0, 100)
            ax4.grid(True, alpha=0.3)

            for bar, value in zip(bars, util_values):
                ax4.text(bar.get_x() + bar.get_width() / 2.,
bar.get_height() + 1,
                         f'{value:.1f}%', ha='center', va='bottom',
fontsize=8)

        # 5. 性能指标仪表盘
        if len(production_line.completed_orders) > 0:
            on_time_rate = np.mean([o['is_on_time'] for o in
production_line.completed_orders]) * 100
            avg_flow_time = np.mean([o['flow_time'] for o in
production_line.completed_orders])
```

```
            throughput = len(production_line.completed_orders) /
(6000 / 3600)
        else:
            on_time_rate = 0
            avg_flow_time = 0
            throughput = 0

        metrics = ['准交率', '吞吐量', '平均流动时间', '平均在制品']
        values = [on_time_rate, throughput, avg_flow_time,
np.mean(wips) if wips else 0]
        units = ['%', '件/小时', '秒', '件']
        colors = ['lightgreen', 'lightblue', 'lightcoral', 'gold']

        y_pos = np.arange(len(metrics))
        bars = ax5.barh(y_pos, values, color=colors, alpha=0.8)
        ax5.set_yticks(y_pos)
        ax5.set_yticklabels(metrics, fontsize=9)
        ax5.set_xlabel('数值', fontsize=9)
        ax5.set_title('实时性能指标', fontsize=11, fontweight='bold')
        ax5.set_xlim(0, max(values) * 1.2 if values else 100)
        ax5.grid(True, alpha=0.3)

        for bar, value, unit in zip(bars, values, units):
            ax5.text(bar.get_width() + max(values) * 0.01,
bar.get_y() + bar.get_height() / 2,
                    f'{value:.1f}{unit}', va='center',
fontweight='bold', fontsize=8)

        # 6. U型布局示意图
        draw_u_line_layout_mini(ax6)
        ax6.set_title('U型生产线布局', fontsize=11, fontweight='bold')

        # 7. 瓶颈工序分析
        bottleneck = production_line.identify_bottleneck()
        if bottleneck:
            ax7.text(0.5, 0.7, '瓶颈工序', ha='center', va='center',
                    transform=ax7.transAxes, fontsize=12,
fontweight='bold')
            ax7.text(0.5, 0.5, f'{bottleneck["process_name"]}',
ha='center', va='center',
                    transform=ax7.transAxes, fontsize=10,
color='red')
            ax7.text(0.5, 0.3, f'利用率:
{bottleneck["utilization"]:.1f}%', ha='center', va='center',
```

```
                    transform=ax7.transAxes, fontsize=9)
        else:
            ax7.text(0.5, 0.5, '无瓶颈数据', ha='center', va='center',
transform=ax7.transAxes, fontsize=10)
        ax7.axis('off')

        # 8. 优化效果展示
        strategy = production_line.optimization_strategy or "基准"
        ax8.text(0.5, 0.7, '优化策略', ha='center', va='center',
                 transform=ax8.transAxes, fontsize=12,
fontweight='bold')
        ax8.text(0.5, 0.5, f'{strategy}', ha='center', va='center',
                 transform=ax8.transAxes, fontsize=10, color='blue')

        if len(production_line.completed_orders) > 0:
            on_time_count = sum(1 for o in
production_line.completed_orders if o['is_on_time'])
            total_count = len(production_line.completed_orders)
            ax8.text(0.5, 0.3, f'准时交付:
{on_time_count}/{total_count}', ha='center', va='center',
                    transform=ax8.transAxes, fontsize=9)
        ax8.axis('off')

        # 9. 仿真进度
        progress = (times[-1] / 6000) * 100 if times else 0
        ax9.barh(0, progress, color='green', height=0.3, alpha=0.8)
        ax9.set_xlim(0, 100)
        ax9.set_xticks([0, 25, 50, 75, 100])
        ax9.set_yticks([])
        ax9.set_xlabel('完成百分比 (%)', fontsize=9)
        ax9.set_title(f'仿真进度: {progress:.1f}%', fontsize=11,
fontweight='bold')
        ax9.grid(True, alpha=0.3)

        plt.suptitle(f'U 型流水线仿真 -
{production_line.optimization_strategy or "基准场景"} - 时间:
{times[-1]:.0f}秒',
                    fontsize=14, fontweight='bold', y=0.98)

        plt.tight_layout(rect=[0, 0, 1, 0.96])

    # 创建动画
    print("创建动画...")
    anim = animation.FuncAnimation(fig, animate,
```

```
                                frames=min(total_frames,
len(production_line.video_data['time_points'])),
                                interval=1000 / fps, repeat=False)

    # 多种保存方案
    print("尝试保存视频...")

    # 方案1: 尝试使用不同的编码器
    success = False

    # 首先尝试保存为GIF (最可靠)
    try:
        print("尝试保存为GIF...")
        anim.save(f'output/{video_name}.gif', writer='pillow',
fps=5, dpi=80)
        print(f"✓ GIF已保存为: output/{video_name}.gif")
        success = True
    except Exception as e:
        print(f"✗ 无法保存GIF: {e}")

    # 方案2: 尝试使用不同的MP4编码器
    mp4_attempts = [
        {'codec': None, 'name': '默认编码器'},  # 不指定编码器
        {'codec': 'mpeg4', 'name': 'MPEG-4'},
        {'codec': 'libx264', 'name': 'H.264'},
        {'codec': 'libx265', 'name': 'H.265'},
    ]

    for attempt in mp4_attempts:
        if success:  # 如果已经成功保存了GIF，可以跳过
            break

        try:
            print(f"尝试使用 {attempt['name']} 保存MP4...")
            if attempt['codec']:
                anim.save(f'output/{video_name}.mp4',
writer='ffmpeg', fps=fps, dpi=100,
                          bitrate=2000, extra_args=['-vcodec',
attempt['codec']])
            else:
                anim.save(f'output/{video_name}.mp4',
writer='ffmpeg', fps=fps, dpi=100, bitrate=2000)
            print(f"✓ MP4已保存为: output/{video_name}.mp4 (使用
{attempt['name']})")
```

```
            success = True
            break
        except Exception as e:
            print(f"✗ 使用 {attempt['name']} 保存 MP4 失败: {e}")

    # 方案 3: 如果所有视频格式都失败，保存为图片序列
    if not success:
        print("所有视频格式保存失败，尝试保存为图片序列...")
        try:
            # 创建图片序列目录
            image_dir = f'output/{video_name}_frames'
            if not os.path.exists(image_dir):
                os.makedirs(image_dir)

            # 保存关键帧
            frame_indices = [0, total_frames // 4, total_frames // 2,
3 * total_frames // 4, total_frames - 1]
            for i in frame_indices:
                frame_idx = min(i,
len(production_line.video_data['time_points']) - 1)
                animate(frame_idx)
                plt.savefig(f'{image_dir}/frame_{i:04d}.png',
dpi=150, bbox_inches='tight')
                print(f"✓ 保存帧 {i}/{total_frames} 到
{image_dir}/frame_{i:04d}.png")

            # 保存最终帧
            animate(min(total_frames,
len(production_line.video_data['time_points'])) - 1)
            plt.savefig(f'output/{video_name}_final_frame.png',
dpi=300, bbox_inches='tight')
            print(f"✓ 最终帧已保存为:
output/{video_name}_final_frame.png")

            success = True
        except Exception as e:
            print(f"✗ 保存图片序列失败: {e}")

    # 方案 4: 如果仍然失败，提供安装建议
    if not success:
        print("\n⚠ 所有保存方法都失败了。请尝试以下解决方案:")
        print("1. 安装 FFmpeg:")
        print("   - Windows: 下载 FFmpeg 并添加到系统 PATH")
        print("   - macOS: brew install ffmpeg")
```

```
        print("   - Linux: sudo apt-get install ffmpeg")
        print("2. 或者安装图像处理库:")
        print("   pip install pillow")
        print("3. 或者使用在线工具将图片序列转换为视频")

    plt.close()
    return success


def draw_u_line_layout_mini(ax):
    """绘制简化的U型布局图"""
    # 简化的U型布局
    u_width = 1.5
    u_height = 1.0
    center_x = 0.5
    center_y = 0.5

    # 绘制U型路径
    theta = np.linspace(np.pi, 2 * np.pi, 50)
    x_outer = center_x + (u_width / 2) * np.cos(theta)
    y_outer = center_y + (u_height / 2) * np.sin(theta)

    ax.plot(x_outer, y_outer, 'k-', linewidth=1, alpha=0.7)

    # 简化工序点
    processes_count = 14
    process_angles = np.linspace(np.pi, 2 * np.pi, processes_count
+ 1)[:-1]

    for i, angle in enumerate(process_angles):
        r = u_width / 2 - 0.1
        x = center_x + r * np.cos(angle)
        y = center_y + (u_height / 2 - 0.1) * np.sin(angle)

        if i < 6:
            color = 'lightblue'
        elif i < 10:
            color = 'lightcoral'
        else:
            color = 'lightgreen'

        circle = plt.Circle((x, y), 0.03, color=color, ec='black')
        ax.add_patch(circle)
```

```
    ax.set_xlim(center_x - u_width / 2 - 0.1, center_x + u_width /
2 + 0.1)
    ax.set_ylim(center_y - u_height / 2 - 0.1, center_y + u_height
/ 2 + 0.1)
    ax.set_aspect('equal')
    ax.axis('off')


def main():
    """主函数"""
    print("开始U型流水线优化分析...")

    # 生成U型布局图
    print("生成U型生产线布局图...")
    generate_u_line_layout()

    # 运行U型线优化场景比较
    print("\n执行问题三：U型流水线优化方案...")
    optimization_results, production_lines =
run_u_line_optimization_scenarios()

    # 绘制优化比较图
    print("绘制U型线优化方案比较图表...")
    plot_u_line_optimization_comparison(optimization_results)

    # 生成优化分析报告
    create_u_line_optimization_report(optimization_results)

    # 为每个优化场景生成仿真视频
    print("\n生成优化场景仿真视频...")
    scenarios = {
        'baseline': '基准场景',
        'u_line_bottleneck': 'U型瓶颈优化',
        'u_line_balanced': 'U型平衡优化',
        'u_line_comprehensive': 'U型综合优化'
    }

    for scenario_key, scenario_name in scenarios.items():
        production_line =
production_lines[list(scenarios.keys()).index(scenario_key)]
        print(f"生成 {scenario_name} 仿真视频...")
        success = create_simulation_video(production_line,
f"u_line_{scenario_key}_simulation", duration_minutes=2)
        if success:
```

```
            print(f"✓ {scenario_name} 仿真视频生成成功")
        else:
            print(f"⚠ {scenario_name} 仿真视频生成遇到问题，请查看上面的错误信息")

    print("\nU 型流水线优化分析完成!")
    print("生成的文件:")
    print("  - output/u_line_layout.png (U 型生产线布局)")
    print("  - output/u_line_optimization_comparison.png (优化方案比较图)")

    # 检查生成了哪些视频文件
    video_extensions = ['.mp4', '.gif']
    for scenario_key in scenarios.keys():
        video_base = f"u_line_{scenario_key}_simulation"
        for ext in video_extensions:
            video_path = f"output/{video_base}{ext}"
            if os.path.exists(video_path):
                print(f"  - {video_path} ({scenarios[scenario_key]}仿真视频)")
                break
        # 检查是否有最终帧图片
        final_frame_path = f"output/{video_base}_final_frame.png"
        if os.path.exists(final_frame_path):
            print(f"  - {final_frame_path} ({scenarios[scenario_key]}最终帧)")
        # 检查是否有图片序列
        frames_dir = f"output/{video_base}_frames"
        if os.path.exists(frames_dir):
            print(f"  - {frames_dir}/ (图片序列)")

    print("\n优化分析报告已在上方显示")


if __name__ == "__main__":
    main()
```